Technology

Chapter 5

Overview of Treatment Technologies

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Learning Objectives

- Have an overview of existing faecal sludge treatment technologies.
- Have an overview of potential future treatment technologies and what information is currently lacking for their reliable implementation. Understand the advantages, constraints and field of application for treatment technologies.
- Be able to compare and contrast different treatment technologies based on performance and appropriateness for local contexts.
- Understand the importance of finding a context-adapted combination of technologies

5.1 INTRODUCTION

In the preceding chapters the characteristics of faecal sludge (FS) were discussed, an introduction to treatment mechanisms was given, and it was described how FS can be collected from the point of storage and delivered to treatment facilities.

In this chapter, an overview and introduction of FS treatment technologies is provided. Each technology has different fields of application. They can be used for the treatment or co-treatment of undigested FS (e.g. from public toilets), or digested or pretreated FS. Given the high content of coarse wastes such as plastics, tissues and paper in the FS discharged by collection and transport trucks, a preliminary screening is needed for most treatment technologies. Also, the characteristics of FS collected at industrial and commercial facilities should be checked as they can be contaminated with metals, have high concentrations of fats, oil and grease, or other concerns as described in Chapter 2. They should be segregated and treated separately. After treatment, three types of endproducts can be distinguished:
- screenings;
- treated sludge; and
- liquid effluents.

Examples of potential combinations of FS and endproducts are presented in Figure 5.1, and are further detailed in the Technology Selection Scheme (see Chapter 17). Selection of the technologies, or combinations thereof, should be done taking into account the local context, existing regulations and the enduse goals (see Chapter 10). Treatment will be comprised of combinations of:

- the treatment of FS directly transported from the onsite sanitation systems - this treatment can be done in one or several steps, and produces solid and liquid endproducts; and
- the further treatment of the resulting endproducts (either the solid part of the treatment endproducts (treated FS) or liquid effluents) before enduse or final disposal.

Additionally, technologies have different fields of application: some can be used either for the treatment or co-treatment of "fresh" FS (e.g. from public toilets), others are better suitable for treating digested FS (e.g. from septic tanks) or pretreated FS. This is related to the fact that fresh FS, derived from bucket or public latrines with a high emptying frequency (once per month or more often), is more difficult to dewater (Chapter 2 and 3) and may produce odors during digestion (Heinss *et al.*, 1998). In order to overcome these problems, fresh FS can be exposed to a chain of treatment technologies, with first a digestion step. Another option is to mix fresh with digested FS. Cofie *et al.* (2006) successfully conducted experiments on unplanted drying beds with a mix of fresh and digested FS at a ratio of 1:2.

In addition to treatment goals, a choice of technologies cannot be made without some form of cost comparison. However, a complete overview of the costs is difficult to obtain as many factors play a role and costs are strongly context specific; moreover, the lack of long-term experience of operational FS treatment implementations further complicates reliable cost estimation. To aid in the selection of appropriate technologies, the last section of this chapter offers insight in the process of cost calculation over the expected life time of technologies, and how costs of faecal sludge management (FSM) and sewer based technologies can be compared.

There are a number of technologies available for the treatment of FS; however, the same level of operational information is not available for all of them based on their varying degrees of implementation and current level of research. In this book, the FS treatment technologies that are covered in an operational level of detail are settling tanks, unplanted drying beds, planted drying beds and co-treatment with wastewater, which are described in detail in Chapter 6, 7, 8 and 9 respectively. Technologies that have also been implemented and are relatively well established are co-composting of FS together with municipal solid waste (MSW); co-treatment of FS in waste stabilisation ponds; and deep row entrenchment. These are described in this chapter under Section 5.2.

Several other technologies have been adapted from activated sludge wastewater treatment and sludge management practises. This category includes anaerobic digestion of FS, sludge incineration, mechanical sludge drying processes such as centrifugation, and chemical treatment through lime addition. These are covered in Section 5.3. Finally, there is a whole range of technologies that are currently under development. Much of this current research has the goal to increase the financial value of treated endproducts, and some of these technologies are also introduced in Section 5.4 and in Chapter 10.

5.2 TREATMENT TECHNOLOGY OVERVIEW

An overview of treatment technologies, together with their treatment objectives and functionality, are presented in Figure 5.1. It is important to realise that for the conversion of FS into a product that is safe for enduse or disposal, several processes need to take place. FS typically contains large volumes of water and hence needs to be dewatered, which can be achieved on its own, or in combination with solid / liquid separation. Depending on the endgoal, further treatment needs could include converting organic matter into a stabilised form and/or pathogen reduction. The underlying mechanisms are described in

Chapter 3. One of the key elements in designing any particular series of technologies is to keep the final goal in mind (see Chapter 10). If the final goal is to make a dry product that can be reused in agriculture, then particular care has to be paid to dewatering and pathogen reduction. If the goal is to incinerate the sludge for energy production, then dryness is very important while pathogens do not play a role (outside of worker protection).

The technology selection scheme (Figure 17.10) provides assistance for selecting technologies that are appropriate for a particular setting, taking into account all role playing factors. Other key elements in selecting technologies, such as economic feasibility are covered at the end of the chapter, and local regulations and local context are discussed throughout the Planning section of the book.

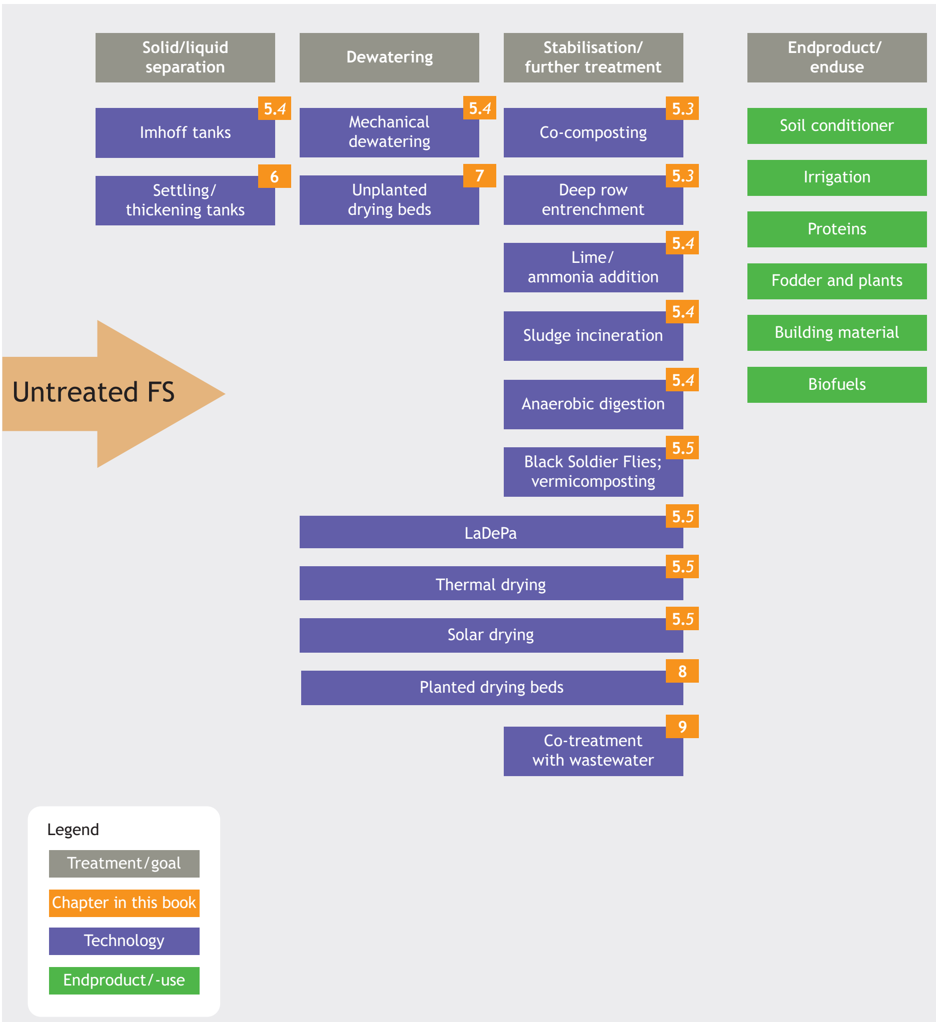

Figure 5.1 Grouping of treatment technologies according to their treatment goal. Endproducts are discussed in Chapter 10. Specific flows from one technology into the next is presented in the Technology Selection Scheme of Chapter 17.

5.3 ESTABLISHED FAECAL SLUDGE TREATMENT TECHNOLOGIES

5.3.1 Co-composting of faecal sludge

Composting is a biological process that involves microorganisms that decompose organic matter under controlled predominantly aerobic conditions. The resulting endproduct is stabilised organic matter that can be used as a soil conditioner. It also contains nutrients which can have a benefit as a long-term organic fertiliser. There are two types of composting systems, open and closed, of which open systems are lower in capital and operating costs but typically require more space. In an open composting system, raw organic matter is piled up into heaps (called windrows) and left for aerobic decomposition. To increase space efficiency, the heaps of waste can also put into walled enclosures which is called box composting. If untreated waste feedstock is placed in a closed container this is called in-vessel or closed drum composting and is considered in the category of closed systems.

To ensure an optimal composting process, the following parameters need to be controlled (EAWAG and IWMI, 2003):

- A carbon to nitrogen ratio (C:N) between 20-30:1 to ensure biological availability; as the organisms degrading organic matter need carbon as a source of energy and nitrogen for building cell structure. High nitrogen enhances ammonia loss due to volatilisation. Higher C:N ratio hinders optimal growth of the microbial populations due to insufficient nitrogen. The compost heap will remain cool and degradation will proceed slowly. High carbon in the final compost product can create problems as microbial activity in the soil may use any available soil nitrogen to make use of still available carbon, thereby "robbing" the soil of nitrogen and thus hindering its availability for plants. During composting carbon is converted to CO and the C:N ratio decreases to a ratio of around 10:1 when the compost is stabilised.
- An oxygen concentration of 5-10% to ensure aerobic microbiological decomposition and oxidation. Aeration can be ensured by either providing passive ventilation structures (air tunnels) or can be enhanced by blowing or sucking air through the waste heap (called active or forced aeration). With forced aeration external energy is required. In open systems mechanically or manually turning the heaps can also contribute to better aeration, although the main objective of this turning is to ensure that material on the outside of the heap is moved to the centre where it will be subject to high temperatures.
- A moisture content between 40 and 60 % by weight to ensure adequate moisture for biodegradation, and that piles are not saturated creating anaerobic conditions. Turning removes water vapour and thus the turning frequency depends primarily on the moisture content of the material, as high moisture content reduces the availability of air in the pore space (Cooperband, 2002). If compost heaps become too dry, water must be added to ensure continuous biological activity.
- A particle diameter of less than five centimetres for static piles. Smaller particles degrade more rapidly as they provide more surface area for microbial decomposition. But on the other hand with smaller particles size aeration through the pile is hindered if structural strength cannot be maintained. Thus particles size influences pore structure and aeration as well as surface area for degradation.

In a properly operated composting heap the temperature rises rapidly to 60-70 °C as heat is released when carbon bonds are broken down in an exothermic process. Pathogen die-off is highest during this time of high temperature. After approximately 30 days, the temperature drops down to 50 °C. During the maturation phase the temperature is around 40 °C, and the process ends once ambient temperature is reached. The whole composting process (including maturation) takes a minimum of six to eight weeks (Klingel *et al.*, 2002).

Optimal composting conditions with appropriate C:N ratio and moisture content can be achieved by mixing different wastestreams together. For example, mixing of FS and MSW for co-composting can be advantageous as excreta and urine are relatively high in nitrogen (see Chapter 2) and moisture, whereas municipal waste can be relatively high in carbon and low in moisture. Concentrations of high lignin materials should be limited as they are resistant to biological degradation. Corn stalks and straw made of a tough form of cellulose are also more resistant to degradation. Although all these materials can be used a higher initial C:N ratio to compensate for lower bioavailability must be considered. A moisture content between 40 and 60% is considered ideal which corresponds to the feel of a damp sponge. Higher moisture content limits air supply, creates anaerobic conditions and results in odor emissions.

Co-composting of FS with MSW is best implemented with sludge that has undergone dewatering (e.g. settling-thickening tanks or drying beds). Although untreated FS can also be used and sprayed over the compost heaps, its high water content will only allow the use of very little volume before the compost heap is too wet and is therefore not practical. Organic MSW usually already has a moisture of 40-60% so typically not much additional moisture can be added before the system gets too wet. In the case of dewatered sludge, FS with a total solids (TS) content higher than 20% is mixed together with MSW in compost piles (Koné *et al*., 2007). For further guidance on ensuring optimal carbon, nitrogen and moisture content, refer to the Sandec website (www.sandec.ch), including the publications: Co-composting of Faecal Sludge and Municipal Organic Waste and Marketing Compost (EAWAG and IWMI 2003) Rouse *et al*. (2008) and Strauss *et al*. (2003).

Potential advantages and constraints of co-composting

The main advantage of co-composting is formed by the thermophilic conditions and the resulting pathogen inactivation. The output of co-composting is a good soil conditioner which provides potential for income generation depending on the demand for compost (see Chapter 10). However, operating a co-composting plant and generating a safe product with value requires technical and managerial skills, which can be limiting if not available.

Case Study 5.1: Co-composting of faecal sludge and organic solid waste in Kumasi, Ghana

(Adapted from Cofie and Koné, 2009)

In February 2002 a research pilot plant was opened in Kumasi, Ghana to study sludge drying in an unplanted drying bed and the subsequent operation of co-composting with organic MSW. For the location the facility of the Buobai treatment plant was chosen. FS was delivered to the plant in trucks, collected from unsewered public toilets and household septic tanks in Kumasi. On the project site, sludge was first dried in unplanted drying beds, as due to its high moisture content, fresh FS is unsuitable for direct aerobic composting. The FS was applied to the beds in a mixture of public toilet and septic tank FS ratio of 1:2. The dried FS was removed from the drying beds once it became spadable (about 10 days) and stored prior to co-composting. For organic waste, the organic fraction of municipal solid waste from markets or residential areas, collected and delivered by trucks to the composting site, was used. The organic fraction of the MSW and dried FS were mixed in a ratio of 3:1 and composted using an open windrow system (aeration by manual turning). During a composting cycle, the following activities were carried out: turning, watering, temperature measurement, weighing and sampling (followed by laboratory analysis). The matured compost was sieved, packed in 50 kg bags and stored prior to reuse - more details are provided in Table 5.1. The compost was tested for its impact on the germination capacity of selected vegetables and the germination capacity varied between 70-100%, which is an acceptable range. A large number of interviewed farmers (83%) were willing to use excreta-based compost.

With regard to helminth eggs, an optimum composting period of at least 2 months was necessary to produce compost that complied with the WHO guidelines of 1 Ascaris egg/gTS. High Ascaris inactivation efficiency (90–100%) was reached after 80 days due to heat generation during the composting process, thus exposing the helminth eggs for more than one month to temperatures over 45˚C . Note that if these conditions are not met, pathogen reduction will not be adequate to meet the WHO guidelines. In that case, one possibility is extended storage prior to enduse.

From the above described investigation, it can be concluded that composting of dewatered FS is technically possible; it results in a soil conditioner safe for use in agriculture. Whether the technology is economically viable, however, depends on various local conditions (see Chapter 10 for issues regarding economic feasibility of endproducts).

Table 5.1 Design criteria and assumptions, used for the pilot-scale unplanted sludge drying bed and co-composting plant in Kumasi, Ghana (Cofie and Koné, 2009)

Faecal sludge dewatering		Co-composting	
Volume of FS treated	45 m^3/month = 1.5 m^3/day	**Ratio MSW:dried FS**	3:1 (by volume)
Dewatering cycles	3 per month	**Composting time**	1 month thermophilic; 1-2 months maturation
FS sludge truck loads	3 per cycle (1 truck ~ 5 m^3)	**Composting cycle**	One starting each month
Ratio public toilet sludge: septic tank sludge	1:2	**Required volume MSW**	3 · 4.5 = 13.5 m^3/month
Surface sludge drying beds	50 m^2	**Raw compost produced**	4.5 + 13.5 = 18 m^3/month
Hydraulic load on beds	30 cm / cycle	**Volume reduction through co-composting**	50%
Dried sludge produced	1.5 m^3 / cycle	**Mature compost produced**	9 m^3/month = 4.5 tonnes/month (density 0.5t/m^3)

5.3.2 Co-treatment in waste stabilisation ponds

Waste stabilisation ponds (WSPs) are widely used for the treatment of municipal wastewater. The mechanisms for stabilisation are based on natural processes that occur in aquatic ecosystems. WSPs are considered to be good options for wastewater treatment in low-income countries when adequate land is available, particularly in tropical climates (Mara, 2004). WSPs consist of several ponds having different depths and retention times.

A combination of three types of ponds in series is frequently implemented in wastewater treatment (Figure 5.2):

1 Anaerobic ponds that are two to four meters deep are used for settling of suspended solids and subsequent anaerobic digestion. The effluent flows to the facultative pond.
2 Facultative ponds that are 1 to 1.8m deep allow for remaining suspended solids to settle. In the top layer of the pond dissolved organic pollution is aerobically digested, while anaerobic conditions are prevalent at the bottom.

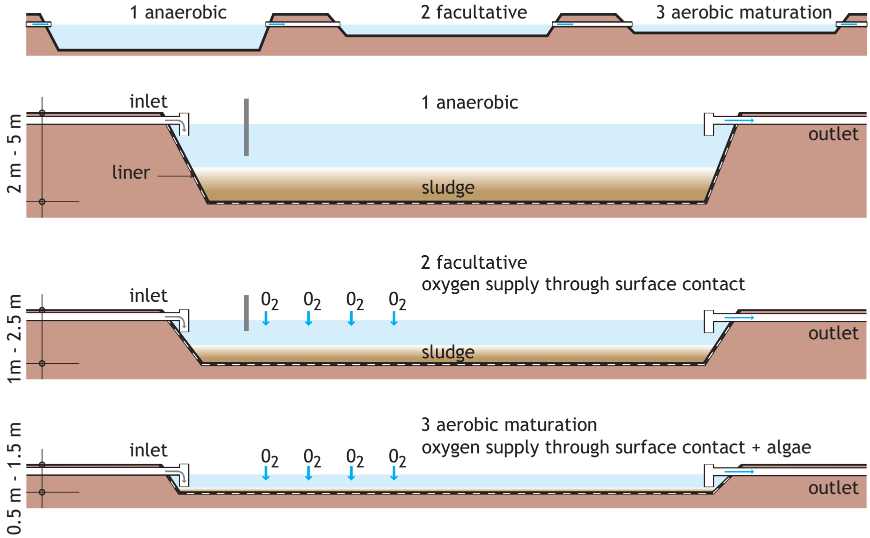

Figure 5.2 Design and principles of the three types of ponds constituting waste stabilisation ponds (Tilley *et al.*, 2014).

3 Maturation ponds that are 1 to 1.5 m deep allow for pathogen reduction and stabilisation. The ponds are mainly aerobic. Oxygen is supplied through algae and diffusion from the air. Pathogen reduction occurs via UV rays from the sun.

With the addition of FS to WSPs, ammonia quickly becomes a limiting factor. Cascade or mechanical aeration can be implemented to ensure adequate oxygen, which also helps to lower the ammonia concentration (Strauss *et al.*, 2000).

Stabilisation ponds are designed for organic loading rates. Anaerobic ponds have 2-3 m depth, remove 60-70 % of BOD and produce limited odor when loaded with 250–350 gBOD/m^3/day. Facultative ponds are 1-2 m deep and loaded with 350 kgBOD/ha/day (35 gBOD/m^2/day; Klingel *et al.*, 2002).

Waste stabilisation ponds can be used for the co-treatment of wastewater with the effluent following solid-liquid separation of FS in settling-thickening tanks. Papadopoulos *et al.* (2007) also applied FS directly after screening, but only in small volumes compared to the wastewater influent. However, problems were observed when dosing FS to the anaerobic pond and dosing was discontinued. Typically, due to the high ammonia concentration and high organic loads and solid content, treating solely FS in WSPs is not recommended, nor is the addition of large quantities (Strauss *et al.*, 2000). WSPs can also be used for the co-treatment of FS with landfill leachate (Kurup *et al.*, 2002), and can treat liquid by-products of other FS treatment technologies, including:

- Leachate from unplanted and planted drying beds. Leachate is low in organic matter compared to domestic wastewater and direct discharge into the facultative pond might be possible as the solid fraction is relatively low. However, the ammonia concentration can still present a problem, and algae and methanogenic inhibition by free ammonia can also occur (as discussed above).

- Effluent from settling-thickening tanks. This was implemented in Argentina as co-treatment with the influent of anaerobic ponds, where tests were conducted for the treatment of the effluent from settling ponds (Fernández *et al.*, 2004; Ingallinella *et al.*, 2002). This solution has also been adopted in Dakar, Senegal, where preliminary solid/liquid separation is done by settling tanks, the effluent is co-treated with wastewater in a WSP, and the thickened sludge is dewatered with unplanted drying beds.

More detailed reading on WSPs, including design, can be found in Mara (2004), Mara *et al.* (1992) and Strauss *et al.* (1999).

Potential advantages and constraints of waste stabilisation ponds

WSPs are simple to build and require relatively low O&M requirements. The technology is appropriate for tropical climates, and achieves relatively high pathogen removal in the effluent. Constraints include land availability, high rate of solids accumulation if preliminary solids separation is not performed, and potential inhibition due to high salt and ammonia concentrations. The removal of sludge that accumulates in the anaerobic ponds may require heavy mechanical equipment (Strauss *et al.*, 2000).

5.3.3 Deep row entrenchment

Deep row entrenchment is a technology that can be considered as both a treatment and enduse option, and is therefore also covered in Chapter 10. Deep row entrenchment was implemented for wastewater sludge in the US in the 1980s and has been adapted for FS in Durban, South Africa (Still *et al.*, 2012). Deep row entrenchment consists of digging deep trenches, filling them with sludge and covering them with soil. Trees are then planted on top, which benefit from the organic matter and nutrients that are slowly released from the FS. In areas where there is adequate land available, deep row entrenchment can present a solution that is simple, low cost, has limited O&M issues and produces no visible or olfactory nuisances. Benefits are also gained from the increased production of trees. However, the availability of land is a major constraint with deep row entrenchment, as is the distance/depth to clean groundwater bodies. In the application in Durban, limited nitrate leaching was found in the soil and tests conducted in the area showed that surrounding groundwater bodies remained free from pollution. It also appeared that the fast growing trees took up the additional nutrients (Still *et al.*, 2012). Deep row entrenchment is considered most feasible in areas where the water supply is not directly obtained from the groundwater source and where sufficient land is available, which means the sludge would have to be transportable to rural and peri-urban areas. In many countries legislation is still lacking for this option; in South Africa for example, environmental regulations will only allow deep row entrenchment for pit sludge disposal at the pilot scale in the foreseeable future.

Potential advantages and constraints of deep row entrenchment

The main advantage of deep row entrenchment is that very little is needed for it: no expensive infrastructure or pumps that are very susceptible to poor maintenance. In addition, growing trees has many benefits such as extra CO_2 fixation, erosion protection, or potential economic benefits. Constraints are that sufficient land has to be available in an area with a low enough groundwater table and, moreover, legislation still needs to catch up in many countries to allow for this technology.

Case Study 5.2: Deep row entrenchment in Durban, South Africa

(Adapted from Still *et al.*, 2002)

The water and sanitation unit (EWS) of the eThekweni municipality in Durban has been pursuing deep row entrenchment for disposal and treatment of both sludge from municipal wastewater treatment and FS derived from ventilated improved pit latrines (VIPs). The EWS project in Umlazi, south of Durban, started operation in 2009. Pit latrine sludge was buried at different loading rates in sandy soils (Figure 5.4; Still *et al.*, 2012). Positive effects were seen on the trees that were planted, however, there where substantial differences depending on the species and experimental conditions.

Figure 5.4 The Umlazi Deep Row Entrenchment Test Site – top the burial of faecal sludge from pit latrines in 1m deep trenches; below an overview picture of the filled trenches with trees planted on top. Groundwater wells were mapped to follow the fate of nutrients, organics and pathogens (photos: Jay Bhagwan, Water Research Council, South Africa).

At a second testing site near Durban it was observed that the relative difference in growth between trees grown with sludge and controls was reduced over time. After one year a 300% increase was observed for the trees growing with FS while at the end of the nine year growth cycle only a 30% to 40% more biomass was obtained, which is still a substantial increase. In addition to nutrients, Ascaris were also monitored. The South African researchers found that while a significant number of helminth ova were found in freshly exhumed pit latrine sludge, after 2.8 years of entrenchment less than 0.1% were found to still be viable (capable of growth or infection, Still *et al.*, 2012).

5.4 TRANSFERRED SLUDGE TREATMENT TECHNOLOGIES

Activated sludge wastewater treatment produces waste sludge that needs treatment. Technologies that are typically applied there may be transferable to application in FSM. The benefit of these technologies is that they have generally been applied for many years and much knowledge is present regarding design, operation and maintenance. The difficulty is however that the application of these technologies to FS has not been researched in much detail yet, which is key for succesful long-term implementation. More details are given per technology.

5.4.1 Anaerobic digestion

During anaerobic digestion, organic matter is converted into biogas and the remaining sludge is referred to as slurry or digestate. Biogas is a mixture of mainly methane and carbon dioxide and the digestate is relatively biologically stable and can be used as a soil conditioner. More information on fundamentals of biogas and its use are provided in Chapters 3 and 10.

Anaerobic digestion treats organic waste in airtight chambers to ensure anaerobic conditions. Anaerobic digestion has been widely applied in centralised wastewater treatment facilities for the digestion of primary sludge and waste activated sludge, typically with plug flow (PFR) or continuously stirred reactors (CSTRs). Anaerobic treatment technologies also include upflow anaerobic sludge blanket (UASB) reactors, anaerobic baffled reactors (ABRs) and anaerobic filters. Anaerobic treatment is also well known and developed for industrial wastes and highly loaded wastewater treatment plants (e.g. agro-industries, Arthur *et al.*, 2011). Throughout Asia, the onsite anaerobic digestion of animal manure with or without the addition of FS is widely practised (Koottatep *et al.*, 2004). However, the potential for semi-centralised to centralised treatment of FS in urban areas still remains untapped. There is great potential for the future development of anaerobic digestion of FS.

The main design parameters for anaerobic digesters are the hydraulic retention time (HRT), the temperature and the loading pattern. Operating conditions that play an important role in the design and operation of anaerobic digesters include:

- solids retention time (SRT);
- HRT;
- temperature;
- alkalinity;
- pH;
- toxic / inhibiting substances; and
- bioavailability of nutrients and trace elements.

When designing an anaerobic reactor, it is important to know the organic load that can be expected, in order to allow for a long enough HRT for degradation to occur. For systems without recycling, the SRT is equal to the HRT (e.g. plug flow reactors). The anaerobic reaction steps are directly related to the length of the HRT: an increase or decrease in the HRT leads to an increase or decrease in the degree of hydrolysis, acidification, fermentation and methanogenesis (Metcalf and Eddy, 2003). It is therefore important to keep track of the HRT to prevent reactor failures. The temperature also plays an important role, especially on the degree and rate of hydrolysis and methane formation. At the same time, temperature also affects physical and chemical parameters in reactors such as gas exchange and solubility of salts, and inactivation of pathogens.

Experience with faecal sludge

There have been a few studies evaluating the anaerobic digestion of FS and excreta. Arthur *et al.* (2011) and Klingel *et al.* (2002) recommend preliminary thickening to reduce the sludge volume and, consequently, the digester size. For the anaerobic digestion of fresh excreta, Daisy and Kamaraj (2011) report in their review that reduction of bacteria and viruses is very well possible, if a long enough hydraulic retention time is chosen. Song *et al.* (2012) found that between 15 and 90 mL biogas/g FS can be produced over 15 to 30°C respectively. However, the gas production only represented a 30% reduction of volatile solids, whereas the theoretical reduction is 50-60%. This indicates that gas production could be higher if operating conditions were optimised.

Potential advantages and constraints of anaerobic digestion for faecal sludge management

Anaerobic digestion has the potential to produce biogas while stabilising FS, reducing sludge volume and odors. However, operation and maintenance (O&M) of anaerobic digesters requires a relatively high level of skilled operation. Inhibition of digestion needs to be considered due to the inconsistent nature of FS, and also detergents and heavy metals should be addressed at the household level. A constraint of anaerobic digestion as a technology for FS treatment is that, despite the vast amount of knowledge on anaerobic digestion, it has not yet been proven for FS alone in semi-centralised to centralised treatment in urban areas. Hence, further research is needed, and pilot scale facilities need to be installed prior to full scale implementation in order to learn more about the safe and sustainable application of this technology.

5.4.2 Imhoff tank

An Imhoff tank is a compact sized tank that combines the effect of a settler and an anaerobic digestion system in one (Figure 5.5). It is a compact system which is well-known for wastewater treatment and has been implemented in Indonesia for FS treatment. Imhoff tanks are most often used as a primary treatment technology in wastewater treatment where it serves as a solid-liquid separation system including partial digestion for the settled sludge. The same considerations for sludge characteristics that were described under anaerobic digestion apply here.

The Imhoff tank is a high-rised tank (up to nine meters for wastewater sludge) where sludge settles at the bottom and biogas produced by the anaerobic digestion process rises to the top. The settling compartment has inclined walls (45° or more) and a slot at the bottom, which allows the sludge to slide down to the centre into the digestion compartment. The gas transports sludge particles to the water surface, creating a scum layer. T-shaped pipes or baffles are used at the inlet and the outlet to reduce velocity and prevent scum from leaving the system. The sludge accumulates in the sludge digestion

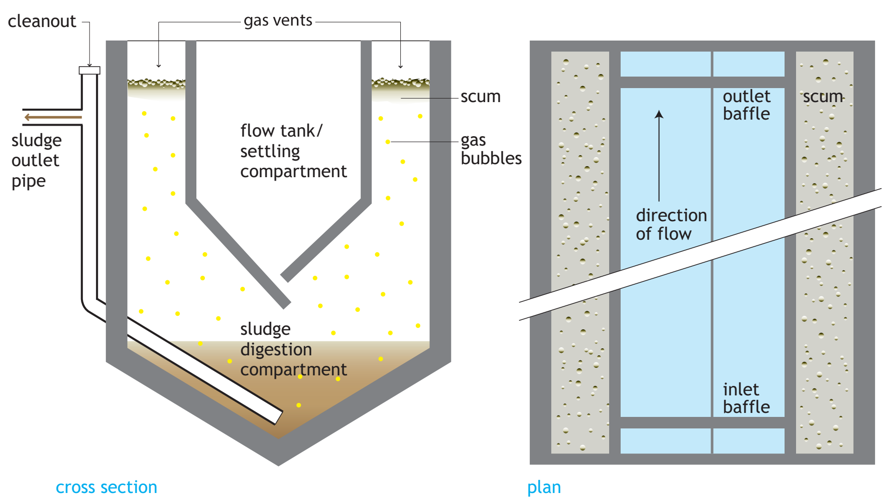

Figure 5.5 Schematic representation of an Imhoff tank (Tilley *et al.*, 2014).

chamber, and is compacted and partially stabilised through anaerobic digestion. The liquid fraction has a short retention time (2 - 4 hours) while the solids can remain up to several years in the digestion chamber. Both the supernatant and the settled sludge need further treatment before final disposal or enduse. The sludge can be further treated in a settling - thickening tank or on a sludge drying bed; the liquid can be treated in for example a constructed wetland. An Imhoff tank can be used when conditions are not favorable for biogas digesters or space for stabilisation ponds is not available.

Dimensioning of the anaerobic digestion compartment depends mainly on the temperature and sludge accumulation and the targeted degree of sludge stabilisation, which are linked to the desludging frequency. The digestion chamber is usually designed for four to 12 months sludge storage capacity to allow for sufficient anaerobic digestion. In colder climates longer sludge retention time and, therefore, a greater volume is needed. The Imhoff tank is usually built underground with reinforced concrete. It can, however, also be built above ground, which makes sludge removal easier because it can be done by gravity. For desludging, a pipe and pump have to be installed or access provided for vacuum trucks and mobile pumps (see Chapter 4). A minimum clearance of 50 cm between the sludge blanket and the slot of the settling chamber has to be ensured at all times. Scum and gas vent chambers are located at the sides of the tank; an outlet for desludging can be added (WSP, 2007; see Figure 5.5). A bar screen or grit chamber is recommended prior to the Imhoff tank to prevent coarse material from disturbing the system.

Potential advantages and constraints of Imhoff tanks

The main advantages of Imhoff tanks compared to settling-thickening tanks are the small land requirement, the possibility of operating only one tank (Klingel *et al*., 2002), and the physical separation between the settled sludge and the liquid fraction. The main constraints compared to settling thickening tanks are the increased operational complexity, slightly higher costs as the Imhoff tanks require an additional elevation to accommodate the inclined baffles, and the risk of damage to the sludge draw-off pipe in case of an inadequate draw-off frequency. Operation and maintenance of an Imhoff system is not as complex as some technologies, but it requires skilled operators. Cleaning of flow paths, the sides of the tank as well as the removal of scum is very important. Stabilised sludge from the bottom of the digestion compartment should be removed according to the design (EAWAG *et al*., 2010).

5.4.3 Sludge incineration

Incineration of sludge is a form of disposal which involves the burning of sludge at temperatures between 850-900 °C. It does not typically take advantage of the potential for resource recovery, however, energy can be captured from the incineration of sludge, for example in cement kilns (see Chapter 10 – Murray Muspratt *et al*., 2014). The ash that is produced from incineration could potentially be used, for example as a cover material for urine diversion dry toilets or in construction, or it can be disposed of in landfill sites. Depending on the source of sludge, the ash may contain high concentrations of heavy metals (Hall, 1999).

Sludge needs to be dewatered prior to combustion, but stabilisation treatment is not necessary as it decreases the volatile content of the sludge (Metcalf and Eddy, 2003). Commonly used incineration systems are multiple-hearth incineration, fluidised-bed incineration and co-incineration with municipal solid waste.

Potential advantages and constraints of sludge incineration

Disadvantages include: the potential emission of pollutants; the need for highly skilled operating and maintenance staff, high capital and O&M costs; and residual ashes (Metcalf and Eddy, 2003). Advantages are that the sludge volume is substantially reduced and all pathogens are removed.

5.4.4 Mechanical sludge treatment

Mechanical dewatering or thickening can be carried out prior to, or following other treatment steps. Dewatering and thickening are important for reducing the volume of sludge that needs to be further treated or managed. After the sludge thickening process, additional reduction of the water content is often necessary and this can be done either naturally or by machine processes such as centrifugation or pressing.

Four technologies that are widely used for dewatering WWTP sludge are the belt filter, the centrifuge, the frame filter press, and the screw press. Only few examples are available in the literature for the implementation of these technologies to FS, but theoretically the technology is transferable. In Malaysia, centrifugation is used to dewater FS after screening and addition of flocculants where there is no space available for more land intensive technologies.

The following technologies are well recognised for wastewater management, and preliminary addition of flocculant is recommend for all of them to facilitate the separation of liquid from the solid particles. Although they are widely used for treating wastewater sludge, further experiments are required before recommendations can be made on design and operation of such systems for FS treatment.

Belt filter press: This allows the water to be squeezed out of the sludge as it is compressed between two belts. The main disadvantages of a belt filter press compared to other mechanical dewatering techniques are the need for skilled maintenance and the difficulty in controlling odors. The system consists of:

- a gravity drainage zone where the flocculated sludge is deposited and conveyed on a porous and mobile belt;
- a compression zone where a second belt is applied on the upper layer of the sludge, and compresses it to a pressure that can reach 7 bars; and
- a zone where the belts are separated and the dewatered sludge is released.

Centrifuge: This technology dries the FS as it is squeezed outwards on the surface of a cylinder rotating around its horizontal axis, due to the centrifugal force. The flocculated sludge is injected into the middle of this cylinder, and the particles are pushed outward against the surface. An Archimedean screw transports the released liquid to the side where the sludge entered, while another transports the sludge to the other end. The main disadvantage of the centrifuge is the high energy requirements.

Frame filter press: This system consists of porous vertical frames fixed in two walls that are positioned in front one of the other to create a chamber. This is a batch process in which the sludge is filled into the chamber at high pressure (up to 15 bars resulting in the leachate being released through the porous frames and the dewatered sludge being released through the opening of the lower wall).

Screw press: A screw press consists of a rotational screw placed in a perforated cylinder. The sludge is loaded at one end, it is pressurised due to a diminishing distance between the screw and the cylinder, and the liquid that is squeezed out is removed through the pores in the cylinder. The dewatered sludge is discharged at the other end. Screw presses provide dewatering at relatively low equipment and operational costs, and minimal maintenance skills are required. However, the dewatering is comparatively lower than other mechanical dewatering technologies.

Potential advantages and constraints of mechanical sludge treatment

The main constraints of these technologies in comparison to non-mechanical options are the investment costs, the O&M requirement, the need to add flocculants and the dependency on electricity. The general advantages are the compactness, and the speed of the process. To transfer these types of technologies to treat FS, information from manufacturers, laboratories, and pilot-scale tests is necessary.

5.4.5 Lime addition

Lime is used for wastewater sludge treatment to achieve the reduction of pathogens, odours, degradable organic matter, and also as sludge conditioner to precipitate metals and phosphorus (Méndez *et al.*, 2002), and has been implemented in the Philippines for FS treatment (Case Study 5.3). The process of pathogen reduction during alkaline stabilisation is based on an increase of pH, temperature (through exothermic oxidation reactions) and ammonia concentration (Pescon and Nelson, 2005). Its effect is enhanced by a longer contact time and higher dosing amount. All chemical compounds which have highly alkaline properties are generally termed as lime. Its most common forms are quick lime (CaO) and slaked lime $Ca(OH)_2$. Quicklime is derived from lime stone by a high temperature calcination process; quicklime is then hydrated to get slaked lime, also known as hydrated lime, or calcium hydroxide (Equation 5.1; Biosolids Technology Factsheet).

Equation 5.1: $CaO + H_2O \rightarrow Ca(OH)_2$

Equation 5.2: $Ca(OH)_2 + CO_2 \rightarrow CaHCO_3 + H_2O$

The high pH due to the formation of $CaHCO_3$ (Equation 5.2) creates an environment that halts or retards microbial degradation of organic matter (Turovskiy and Mathai, 2006). However, it is important to consider a number of design parameters like sludge characteristics, lime dose, contact time and pH in order to achieve optimum results from lime stabilisation in the most economic way possible (Turovskiy and Mathai, 2006).

An added benefit of lime is that heavy metals can precipitate with the lime. However, the pathogen removing effect of lime also affects desired microbial processes such as composting and other soil processes. Moreover, safety is very important: as lime is corrosive to the skin, eyes and lungs and proper personal protection equipment (PPE) is crucial (see also Case Study 5.3). Furthermore, protection from fire and moisture must be ensured.

Potential advantages and constraints of lime treatment

The main disadvantages of this technique are the requirement of consumables (lime), and a dry storage area. Pathogen regrowth is also a concern. Lime is an alkaline material which reacts strongly with moisture and high risks of hazard to the eyes, skin and respiratory system are observed. Therefore, skilled staff is required who must follow health and safety procedures and make use of good protective equipment.

Case Study 5.3: Lime stabilisation in the Philippines, San Fernando Valley

(Adapted from Robbins, 2009)

In June 2008, engineers and staff from the San Fernando City Health, Planning, Environment and Engineering offices engaged in the first stage of a pilot demonstration project to determine the effectiveness of lime stabilisation as a method of treating domestic FS from septic tanks in the Philippines (Robbins, 2009). Lime treatment was also mentioned as an appropriate technology by the Philippine's Department of Health (DOH) but it was not tested before in the field.

In the start-up of the study, one load (approximately $5m^3$ of FS) was used in a test run. First, a proper site had to be selected, using the following criteria: 1) the site is at a sufficient distance from residential areas; 2) the groundwater table is more than 25m below the testing site, and 3) preferably the soil is impermeable to reduce lining costs. After this site was identified, a mixing pit was created. The mixing pit in the San Fernando study was excavated to a depth of 1.5 meters and was 3 meters wide by 4 meters long. The soils at the landfill are high in clay particles, hence no liner was required.

FS was transported to the testing site by truck, and dumped into the pit in one off-loading. After filling the pit to the required level, lime was added and mixed. Lime was delivered at the site by the supplier in 50 kg bags. The lime was added manually one shovel-full at a time and by wearing dust masks the workers prevented breathing in the reactive powder. Then the lime was mixed into the FS. Although a small three horsepower mixing pump was available, manual mixing was performed: two to three operators kept the lime in suspension for 30 minutes with large wooden paddles. This time span proved to be sufficient to reach the desired level of mixing. It is suggested that an alternative way of mixing could be to add the lime directly into the tank of the truck. The progress of the treatment was monitored with a handheld pH monitor and a stop watch. To reach proper disinfection, the following goal had to be achieved: 30 minutes at pH 12; 60 minutes at pH 11.5; or 120 minutes at pH 11. The speed of the pH rise and the ultimate level of the pH will depend upon the amount of lime used per m^3 of FS, the quality of the hydrated lime, and the mixing. The San Fernando trials show that an application rate of 50 kg of lime per $5m^3$ of FS was adequate to achieve the required level of treatment (pH 11 for 2 hours). After that period, full pathogen destruction was observed as well as a proper solid liquid separation. Tests performed on other parameters such as heavy metal content revealed that the levels remained all under the limits set by the DOH of the Philippines.

After the process was completed, the pH decreased again toward neutral. After 24 hours, the clear liquid was siphoned off and discharged to a leachate pond and it could then be used to irrigate agricultural land, or for landscaping purposes. The solids may be applied as a soil amendment or dried and used for example as a cover for sanitary landfills.

For the San Fernando study, the cost of the hydrated lime was 455 Philippine Pesos (9 USD) per 50 kg bag, including delivery. Taking into account two employees, monitoring, excavation and miscellaneous costs, the total cost for treatment was approximately 200 Philippine Pesos (4 USD) per m^3 of FS treated. The results, costs and applicability make lime stabilisation a feasible technology for FS loads up to 15 m^3.

5.5 INNOVATIVE TECHNOLOGIES FOR FAECAL SLUDGE TREATMENT

There is currently a great deal of of research being conducted on innovative FS treatment technologies. Many of these innovations incorporate resource recovery, and this section therefore has a strong link with Chapter 10, Enduse of Treatment Products.

5.5.1 Vermicomposting

Earthworms are a member of the oligochaetes sub-class and they appear to be very effective in organic waste reduction. An example is the “vermi-filter”, which treats diluted domestic wastewater sludge in a system inoculated with earthworms (Zhao *et al.*, 2010). Interestingly, the earthworms seemed to function in synergy with bacterial communities within the filter. Worms cannot survive in fresh faeces and need some kind of support in the form of layers of soil and vermi-compost. Vermicomposting is not a reliable method to ensure adequate pathogen removal. However, when carried out under proper conditions the technology of vermicomposting can lead to a complete removal of coliforms. Rodríguez-Canché *et al.* (2010) found helminth egg removal in experiments with vermicomposting on septic tank FS. Permissible levels for reuse in agriculture were achieved after 60 days, starting from the initial earthworm inoculation, faecal coliforms, Salmonella spp., and helminth ova were reduced to <1000 MPN/g, <3 MPN/g, and <1 viable ova/g on a dry weight basis, respectively.

Potential advantages and constraints of vermicomposting

In general, the advantages and constraints for vermicomposting are similar to the points for co-composting. However, vermicomposting cannot be carried out at the thermophilic temperatures of co-composting. Therefore if adequate pathogen reduction is not achieved during treatment, further treatment steps are required. Constraints are that the technology is still in development; the worms can be quite susceptible to toxic components (or higher concentrations in general), and the time span until matured compost is reached can be longer than for thermal composting. The production of worms can be beneficial provided there is a market for them.

5.5.2 Black Soldier flies

The Black Soldier fly (*Hermetia illucens*) originated in America, but is commonly found in temperate and warm climates. The fly larvae feed on decaying organic material, such as vegetables and fruits, or manure. The Black Soldier fly (BSF) larvae have been investigated for the degradation of organic wastes such as municipal solid wastes, animal manure, and FS (Diener *et al*., 2009; Diener *et al*., 2011; Qing *et al*., 2011). This process relies on the natural growing cycle of BSF which need to feed only during the larval stage, then migrate for pupation, and do not feed anymore, even during the adult stage. Therefore, the risks of the BSF being a vector for disease transmission is very low, as it is not attracted by decaying organic matter when it can fly (Sheppard *et al*., 1994). During their larval stage, BSF larvae achieve a rapid reduction of organic waste volumes of up to 75%, together with the removal of nutrients such as nitrogen and phosphorus (Diener *et al*., 2009). This growth stage can vary from two weeks to four months depending on the availability of food, and thus allows for the treatment of wastes even when waste is not produced continuously.

BSF larvae have been shown to grow well solely on FS; however, Diener *et al.* (2009) observed that a mixture of FS and municipal solid waste can achieve higher and faster larvae mass production. This can be advantageous for the selling of the larvae as animal feeding to farmers (see Chapter 10). The FS residue remaining after the BSF larvae feed need to be further composted or anaerobically digested to produce a soil conditioner.

Figure 5.6 Black Soldier fly pre-pupae (photo: Stefan Diener).

Most of the work so far has been at a laboratory scale. Yet, the market seems to be developing. For example, the Biocycle company is working on upscaling a profitable business model by collecting human waste, treating it at their facilities, harvesting the larvae and preparing the product for sale (www.biocycle.com). Low operation costs of this technology and the market potential (crushed dried larvae as protein source) make it a promising technology. Some technical as well as entrepreneurial questions however are still to be answered.

Potential advantages and constraints of Black Soldier flies

The advantage of using BSF for treatment of FS is that it can be achieved with or without mixing with other organic wastes, and on a small scale. It allows revenue generation for small entrepreneurs with minimal investment. However, information on upscaling experience in low- and middle-income countries is not yet available, and therefore precise recommendations on the design and operation of this technology cannot be given for FS treatment (Diener *et al.*, 2011).

5.5.3 Ammonia treatment

Ammonia treatment can be applied for pathogen reduction. Pathogen inactivation by uncharged ammonia (NH_3) has been reported for several types of microorganisms, bacteria, viruses and parasites (Jenkins *et al.*, 1998; Pescon and Nelson, 2005). The principle of pathogen reduction with ammonia is based on the fact that ammonia (NH_3) enters cells, takes up intracellular protons for the formation of ammonium (NH_4^+) and as a charged ion disturbs the functioning of organisms (Park and Diez-Gonzalez, 2003). Ammonia addition to sludge has been applied for wastewater sludge, where it is commonly referred to as alkaline stabilisation (Allievi *et al.*, 1994; Mendez *et al.*, 2002).

More recently, investigations have been conducted on using the ammonia from excreta for pathogen reduction in FS. This can be done by collecting urine separately, and then mixing it with FS, as urine has a high ammonia concentration (Chapter 2). For sludge with low ammonia concentration, additional ammonia in the form of the synthetic urea can be added to enhance the treatment.

Potential advantages and constraints of ammonia treatment

In comparison to lime treatment, ammonia requires less stringent storage conditions. It seems particularly applicable in areas with urine diverting dehydrating toilets (UDDTs). In the cases where synthetic urea needs to be applied, the costs become higher, which may limit the economic feasibility and sustainability of the technology. Another constraint is the stability of nitrogen in treatment endproducts, and whether the full nutrient benefit can be achieved.

Case Study 5.4: Sanitisation by ammonia – die-off of Ascaris and the Safe Sludge project

To evaluate the pathogen reducing effect of ammonia, Fidjeland *et al.* (2013) monitored the viability of Ascaris eggs from FS during storage at laboratory scale at different ammonia concentrations and temperatures. At ammonia concentrations above 170 mM and 23 °C, 99.9% reduction of Ascaris egg viability could be achieved within 1.5 month - this corresponds to 2 L flush water per person and use. For flush water volumes of 6 L per person and use, the ammonia concentrations were lower (44 mM) and 6 months storage was required at 23 °C. At higher temperatures, the inactivation of Ascaris eggs was faster and the required ammonia concentration lower. By implementing toilet systems which use airtight storage and low flush water volumes, the intrinsic ammonia may be sufficient to sanitise the FS without additional treatment.

Another project called "Safe Sludge" was carried out from May 2011 until May 2013. The goal was to achieve the pathogen reduction of FS from urine diverting dry toilets (UDDTs) with the ammonia that is naturally present in urine. UDDT sludge is much drier with smaller volumes than most FS. This process appears to be more effective for UDDT sludge as it facilitates the contact time between ammonia and the pathogen containing faeces and no synthetic urea needs to be added. The urease enzyme is not active above a pH of around 9. As a result, the Safe Sludge disinfection process requires two stages: a 4-hour contact time for urine and faeces to hydrolyse urea, followed by the addition of an alkalinising agent (calcium hydroxide) to produce ammonia.

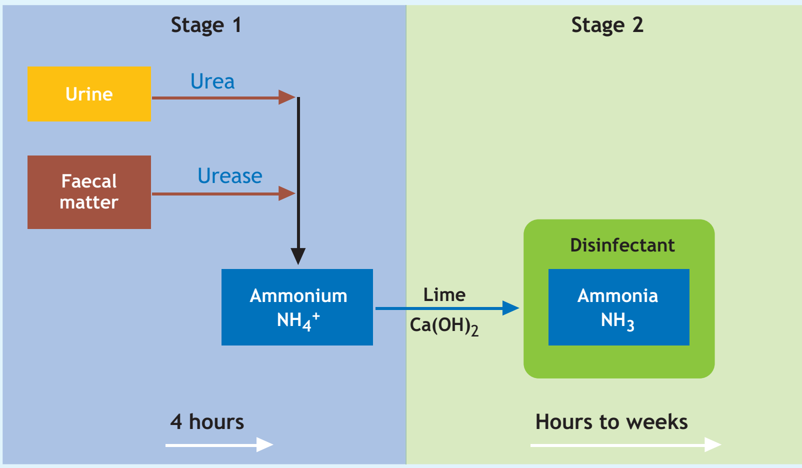

Figure 5.7 The Safe Sludge two stage disinfection process: hydrolysis of urea catalysed by urease (up to 4 hrs) and lime addition to increase pH and so achieve ammonium conversion into ammonia, a known disinfectant (estimated desinfection time: hours to weeks). Figure adapted from http://forum.susana.org (2013).

5.5.4 Thermal drying and pelletising

Thermal drying allows the removal of all types of liquids from FS (see Chapter 3). It has been applied in the management of wastewater sludge for many years, and the technology has been taken up and improved from its original application in other industries (e.g. paper industry). Several types of technologies exist, all based on the ability of evaporating water with heat. The endproducts are stable and in a granular form allowing easier storage or transport.

Direct or indirect thermal dryers are also referred to as convection or contact dryers, respectively (Lowe *et al.*, 2007). These systems require preliminary dewatering if used for sludge that is high in water content. In direct thermal driers, the hot air or gases are mixed with the dewatered sludge, as they pass through it, or are transported with it. In indirect thermal driers, a heat exchanger is used, which allows the heat convection to the sludge. In this case, the heat carrying media is often steam or oil, and does not come in direct contact with the sludge, which reduces the operational need to separate the sludge from the heat carrier. In both cases, the vapor produced by the evaporated water needs to be collected and transported out of the dryer. Gas treatment can be an issue depending on environmental requirements and the odors produced. Indirect thermal dryers produce less contaminated vapor.

Potential advantages and constraints of thermal drying

Thermal drying results in a significant reduction in volume as well as pathogen content. Dried sludge is easy to handle and to market, and can be used in agriculture (see Chapter 10). The main constraints are the expense, high energy requirements, the potential risks of fire or explosion due to the gas and dust in the system, and the high maintenance requirements.

Pelletising combines mechanical dewatering and thermal drying technologies. The dried pellets can then be used as an energy source or soil conditioner, and are relatively easy to transport and to market. Case studies 5.5 and 5.6 present examples with FS to produce a soil conditioner and fertiliser.

Case Study 5.5: Pellets as soil conditioner/fertiliser

(Adapted from Nikiema *et al*., 2013)

In Ghana, experiments were carried out with dried FS to produce five different types of products, which were subsequently pelletised using locally constructed machinery (a version of a 380V pelletiser). As a source of dried FS, public latrine sludge was mixed with septic tank sludge in a 1:2 ratio dewatered and stabilised in an unplanted drying bed and co-composted (Nikiema *et al*., 2013). A number of key operating parameters were identified: moisture content (10-55% in mass) and binder type and concentration (clay or starch - 0-10% in mass). Output parameters were the amount of high-quality pellets that were generated, and the length and stability of pellets.

From preliminary investigations cassava starch and clay were identified as possible binding materials, of which cassava starch proved to be the better candidate. Nikiema *et al*. (2013) recommend pre-treating the starch through the addition of hot water (85 ± 5 °C) to dry the starch under manual stirring; a 3% mixture is recommended for addition to dried sludge to obtain the best pellets.

Case Study 5.6: Pelletising LaDePa machine from Durban, South Africa

Another example of combining drying and pelletising is the LaDePa (Latrine Dehydration and Pasteurisation) system developed by eThekwini Water and Sanitation (EWS, Durban, South Africa) in conjunction with their technology partner Particle Separation Systems. Here, a technology has been developed that can treat FS from pit latrines over a number of subsequent thermal and mechanical treatment steps. It separates detritus from dewatered sludge via screws which deposit pellets on a moving belt. These pellets are dried with air at 100 °C (the so-called “Parsep dryer”), and pathogen reduction is achieved by means of medium wave infrared radiators. Although this is energy intensive, the energy consumption per person equivalent is approximately half of what a conventional activated sludge wastewater treatment plant consumes. After several modifications and redesigns the LaDePa is now available in modular form (in one container) to treat any sludge between 20 – 35 % solids and to pasteurise it to an 80 – 90 % solid product. The pellets can be sold and used as a fuel or as a soil amendment.

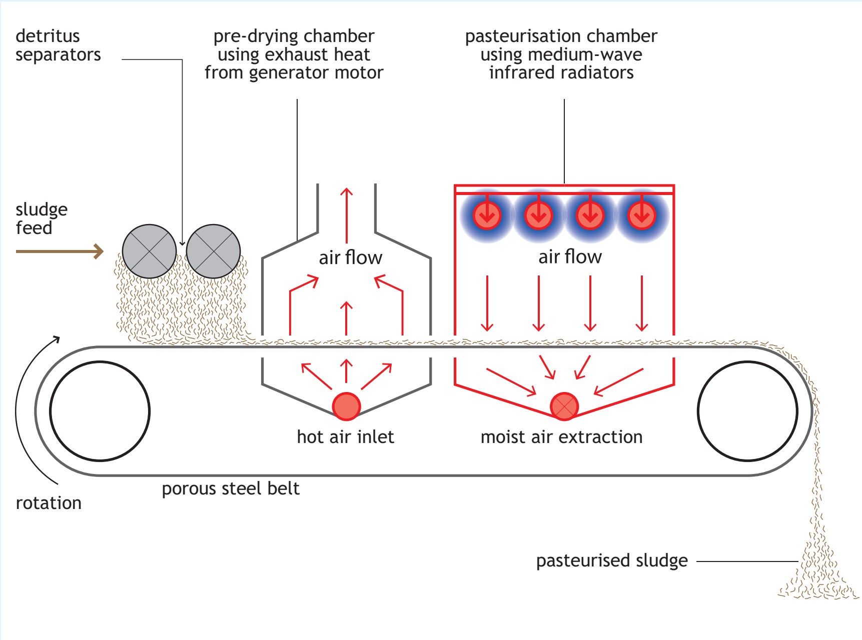

Figure 5.8 Schematic representation of the LaDePa machine.

A significant advantage of the LaDePa machine is that is designed to treat pit latrine sludge without any (manual) pre-sorting. Commonly, pit latrine sludge contains quite a high amount of non-organic municipal solid waste (see also Chapter 2, Section 2.9.7), which complicates treatment and the rendering of a useful product, but the LaDePa is able to remove the detritus.

Potential advantages and constraints of sludge drying and pelletising

The main advantages of these technologies are that they are compact, mobile and robust. Moreover, depending on which processes are used, the pellets are free from pathogens and therefore safe for agricultural use. Pellets can also be used as a dry fuel in industrial combustion, regardless of the pathogen content. However, in case of a breakdown of the system, costs and skilled knowledge requirements may be high. Moreover, the main constraint of mechanical drying and pelletisiing is the dependency on electrical power. The energy use, capital costs, and specialised knowledge required for maintenance are other drawbacks.

5.5.5 Solar drying

A special form of drying is applied in solar sludge driers. They also have been used on a large scale since the nineteenth century in Europe and USA for the treatment of wastewater sludge (Hill and Bux, 2011). This technology is generally constructed in greenhouse structures with transparent covers, concrete basins and walls. Sludge is disposed into these basins and processed for about 10 to 20 days. Options exist for batch or continuous operation, with devices to control the conditions in the greenhouses (e.g. ventilation, air mixing, temperature). The main factors influencing the evaporation efficiency in these systems are the solar variation, the air temperature and the ventilation rate, with initial dry solid content of the sludge and air mixing also influencing the process (Seginer and Bux, 2005). Short wavelengths light such as UV is blocked by the cover. Therefore, the pathogen reduction efficiency is slightly reduced, especially for faecal coliforms that are very sensitive to UV (Shanahan *et al.*, 2010). Final dried solid content of about 40% (after 12 days drying) up to about 90% (after 20 days drying) were found under different conditions by Shanahan *et al.* (2010) and Hill and Bux (2011) respectively.

Potential advantages and constraints of solar drying

The main advantages of this option are the low energy requirements, the limited complexity of the technology and low investment costs, and the high potential dewatering efficiency. The main constraints are the space requirements and the need for mechanical means to turn the sludge, as well as to ventilate the greenhouses. Although pilot tests are being carried out, for the moment no information is available on the use of this technology for the treatment of FS in low-income countries or on design and operating parameters that need to be considered for this purpose.

5.6 SELECTING TREATMENT TECHNOLOGIES

This chapter has provided an overview of treatment technologies. When selecting the optimal treatment and/or combinations of treatments, many factors have to be considered, which is complicated by the lack of long-term operating experience. The Technology Selection Scheme and FSM Planning from A to Z presented in Chapter 17 are designed to aid in this selection. In addition, Box 5.1 provides information on how to compare costs of treatment technology options.

Box 5.1: Cost comparison of treatment technology options

Linda Strande

Outlined in the Planning Section are all of the steps that need to be taken during the decision-making process, and Chapter 17 Planning Integrated FSM Systems summarises all of the steps in the Technology Selection Scheme (Figure 17.10) and FSM Planning from A to Z (Table 17.1). In addition, Chapter 13 explains different models of financial flows, and Chapter 12 explains different models of management. A cost comparison cannot be made outside of an integrated approach that includes Management and Planning, as the costs of Technology are directly interrelated and impacted by these other factors. Costs need to be compared on a life-cycle basis, i.e. over the planning horizon of the project, including all recurrent expenditures (e.g. transport, O&M, capacity-building and policy development). It is not only the cost that is important, but by whom and how it will be paid over the long-term. The best option is not always the cheapest, but that which ensures household satisfaction, broad coverage and cost recovery (see Section 17.5). Ultimately, the success of a FSM plan largely depends on the capacity of the stakeholders to enforce the financial mechanisms that have been planned, and the capacity of the stakeholders to operate and maintain the FSTP.

The difficulty of comparing the costs of FSM technologies presented in this chapter, are that they are mostly operational at the laboratory or pilot scale, and there is no long-term operating experience on which to base estimates on. Access to this cost data will improve overtime with increased installations, but in the meantime reasonable estimates have to be calculated. Another difficulty is the heterogeneity of costs from one context to the other.

There are two ways to calculate costs over the expected lifetime:

1 Net Present Value (NPV): this calculation entails determining the required capital investment, and all future cash flows over the expected lifetime. This amount is then converted to the present worth, i.e. the amount of money that would need to be invested today to cover all expenses during the lifetime. The lower the sum, the less expensive the option is. This value can be used to compare options with equivalent lifetimes.

2 Equivalent Annual Cost (EAC): this calculation entails determining the required capital investment, and all future cash flows over the expected lifetime. This amount is then converted to the amount of money that would be required on a yearly basis over the expected lifetime. The NPV can be converted into an EAC, and vice versa, but EAC can be used for comparisons among technologies with different lifetimes. Annual costs are calculated as the annualised capital cost over the expected lifetime with interest rate, in addition to annual operations and maintenance costs as shown in equation 5.3:

Equation 5.3:

$$AC_o = -C_o \left[\frac{(1+i)^{n_o} \cdot i}{(1+i)^{n_o} - 1} \right] - F_o$$

Where:

AC_o = annualised cost of sanitation system component (USD/capita/year)

C_o = capital cost of sanitation system component (USD/capita)

n_o = service lifetime of sanitation system (years)

i = real interest rate

F_o = annual operating cost of faecal sludge management system component (USD /capita/year)

Another possibility for comparisons among systems is to normalise the costs to tons of total solids treated. An example of estimating costs based on a pilot scale is provided by Steiner *et al.* (2002) based on planted drying bed research conducted in Thailand by Koottatep *et al.* (2001) and Surinkul (2002). Based on construction and operation during the pilot phase, annualised costs were estimated to be 1,500 USD/year (0.95 USD per capita or 186 USD per ton of total solids). Ongoing operations and maintenance (e.g. harvesting plants, sludge removal) were not included, but could be forecasted based on operation during the pilot.

This estimate only included the cost of the drying bed, and not the onsite containment system at the household level, collection and transport, or enduse of treated sludge and leachate. A comparison of complete FSM and sewer based systems, and how the costs are borne is provided by Dodane *et al.* (2012) and summarised in Table 5.2. The analysis was done based on existing side-by-side operational systems in Dakar Senegal. To compare FSM and sewer based systems, the entire service chain needs to be considered. When costs for the entire service chain are estimated, it is critical to evaluate by whom the costs will be borne (e.g. household, government, private sector).

Table 5.2 Comparison of FSM and sewer based systems on existing side-by-side operational systems in Dakar, Senegal (Dodane *et al.*, 2012)

ANNUALISED CAPITAL COSTS (PER CAPITA*YEAR)									
	SEWER BASED (SB)				FAECAL SLUDGE MANAGEMENT (FSM)				
	House	ONAS	Enduser	TOTAL	House	C&T	ONAS	Enduser	TOTAL
Household Connection[1]	0.00	-4.98	0.00		-2.74	0.00	0.00	0.00	
Collection Conveyance[2]	0.00	-30.20	0.00		0.00	-0.28	0.00	0.00	
Treatment Plant[3]	0.00	-7.49	0.00		0.00	0.00	-1.03	0.00	
TOTAL	0.00	-42.66	0.00	**-42.66**	-2.74	-0.28	-1.03	0.00	**-4.04**
ANNUAL OPERATING COSTS (PER CAPITA*YEAR)									
	SEWER BASED (SB)				FAECAL SLUDGE MANAGEMENT (FSM)				
	House	ONAS	Enduser	TOTAL	House	C&T	ONAS	Enduser	TOTAL
Collection Conveyance[4]	0.00	-6.64	0.00		-5.00	0.26	0.00	0.00	
Sanitation Tax[5]	-2.00	2.00	0.00		-2.00	0.00	0.00	0.00	
Treatment Plant[3]	0.00	-6.46	0.00		0.00	0.00	-0.84	0.00	
Valorisation Endproducts[6]	0.00	1.13	-0.01		0.00	0.00	0.01	-0.01	
TOTAL	-2.00	-9.97	-0.01	**-11.98**	-7.00	0.26	-0.83	-0.01	**-7.58**
CAPITAL AND ANNUAL OPERATING COSTS COMBINED (PER CAPITA*YEAR)									
TOTAL	-2.00	-52.63	-0.01	**-54.64**	-9.74	-0.02	-1.86	-0.01	**-11.63**

1 Household Connection (capital) = household sewer connection, septic tank
2 Collection Conveyance (capital) = sewer, pumping stations, vacuum trucks
3 Treatment Plant (capital and operating) = wastewater treatment plant, faecal sludge treatment plant
4 Collection Conveyance (operating) = sewer, pumping stations, onsite emptying fee, truck transport
5 Sanitation Tax (operating) = sanitation tax paid by every resident based on water consumption
6 Valorisation End-products (operating) = biogas, reclaimed water, biosolids

As will be discussed in Chapter 14.5.3, the comparison of treatment technologies is also complicated by factors such as the level of centralisation or decentralisation. FSM technologies tend to be more decentralised or semi-centralised than centralised sewer-based systems. In terms of meeting long-term urban growth requirements, decentralised technologies are more flexible as they can be built in a modular basis as needed (Maurer, 2009). On a management and capital cost basis, the economy of scale results in larger plants being more cost effective than smaller plants. However, when haulage of sludge is taken into account, it appears that smaller decentralised plants are more affordable as travel distances and time can be reduced. For this reason, it is important to consider the whole supply chain when making a decision. The correlation between scale and cost is not linear, and typically a breakeven point can be found. For example, in Japan decentralised wastewater treatment including reclamation is more affordable than conventional dual-pipe water delivery and sewer systems at flows greater than 100 m^3/day (Gaulke, 2006). All of these factors are very dependent on the local context and the specificities of each city (see Section 14.4.8).

5.7 CONCLUSIONS

As shown in Figure 5.1, this chapter provided an overview of established and emerging technologies for FS treatment. Important points to consider when selecting technologies include that there are different technologies for different treatment objectives, and they can be employed alone and/ or in combination. There are many factors to consider when selecting optimal treatment configurations, including final enduse, treatment objectives, potential advantages and constraints, and how to compare costs. Further material is covered in the management and planning sections of this book.

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