

3

Faecal sludge sample collection and handling

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OBJECTIVES

The objectives of this chapter are to:

- Select different sampling techniques depending on objectives
- Select sampling devices and locations
- Develop appropriate and reliable faecal sludge sampling schemes and plans
- Ensure sample representativeness and integrity
- Protect health and safety of employees and users of onsite sanitation.

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3.1 INTRODUCTION

Quantities and qualities (Q&Q) of faecal sludge vary significantly along the entire faecal sludge management (FSM) service chain. Further understanding of factors such as biodegradability, nutrient content, pumpability, dewaterability, resource recovery potential, pathogens, and potential inhibitory compounds are all particularly important for effective faecal sludge planning and management. Sampling is the action or process of taking a subset of a larger volume for characterisation. This process assumes that samples are representative of the larger volume, and there are measures to put in place to help ensure this. Therefore, a proper sampling scheme and subsequent analysis of faecal sludge is paramount for sustainable FSM. As introduced in chapters 5 and 6, the modelling of onsite sanitation will also help to bring a more systematic approach to data collection and sampling, and the number of parameters of interest will continue to grow, resulting in increased demands for sampling and analytical work.

How and where samples are taken, transported, and analysed depends on the specific objectives of the sampling. Examples of sampling objectives include designing a treatment facility, planning for emptying and transport services, evaluating rates of sludge accumulation, selecting and operating treatment processes, evaluating resource recovery options, and complying with regulatory requirements. Sampling and sample handling need to be carried out in such a way that the respective traits being measured (*i.e.* volumes, characteristics) are as similar as possible during the analysis as when the sample was taken. Analysis of samples can be done either *in situ* (*e.g.* within containments), in the field, or in a laboratory after being transported. Proper preservation help ensure that no significant changes in composition occur before the analyses are made. To ensure representativeness of collected data, emphasis is also placed on proper sample collection and tracking. A preliminary site visit, or familiarity with sampling locations, is necessary prior to any survey, sampling, or analysis decisions being made. Furthermore, sampling and sample handling need to be carried out in such a way that is safe for the people collecting and analysing the samples. Examples of safety aspects that

need to be considered include collapsing pit latrines, falling or tripping hazards, working in confined spaces, asphyxiation, and hygiene. These topics are all presented in more detail in this chapter.

3.2 SAMPLING OBJECTIVE

The sampling objective is the defined purpose for collecting the data, which analysis of the samples will provide. Identifying the sampling objective is the first step in a sampling campaign. The next step is to develop a sampling plan specifically to answer the question you are asking. Sampling locations, frequency, timing, tools, and methods can greatly affect the outcome. For example, if you are interested in how faecal sludge accumulates within pit latrines, it would not necessarily make sense to sample what collection trucks are discharging at a large-scale treatment facility. However, if you want to improve the operation of a treatment facility, then directly sampling what is being discharged does make sense. Faecal sludge can be sampled for analysis at each step of the sanitation service chain depending on the question, for example, directly from the containment, from the collection vehicles, or during and after treatment. Each location and sampling purpose comes with different considerations. Below are examples of sampling strategies that are relevant to different sampling objectives. These are presented in the sequence of the sanitation service chain.

3.2.1 Containment

Estimating rates of accumulation at the community to city-wide scales

If the objective is to understand actual rates of accumulation that are occurring at a community to citywide scale, then it is logical to measure *in-situ* volumes and estimate time periods for the accumulated sludge. This is in contrast to measuring what is delivered to a treatment plant, which is probably less than the total accumulated amount. Accumulation rates are important for planning purposes, and for designing treatment technologies. For more information on how to develop a sampling campaign to estimate rates of accumulation, refer to Chapter 5.

Evaluating faecal sludge stabilisation with location and time in onsite sanitation systems

If the objective is to understand how faecal sludge changes with location and time within containment in order to improve management, then sampling should take place directly within the containment, for example at various depths and/or times. However, logistically this might be quite difficult. In addition, the *in-situ* environment is altered during an emptying operation, making it very difficult to analyse what is actually occurring underground. Therefore, assumptions might need to be made; for example, that taking samples every 300 mm while the containment is being emptied is representative. This needs to be managed with logical and transparent assumptions.

3.2.2 Collection and transport

Planning of emptying services for a community

If the objective is to design emptying services, then it is important to be able to select an emptying technology that is compatible with the sludge thickness; for example, if the sludge is too thick then a gulper (or manual pump) might need to be used instead of a vacuum pump. It is also important to have adequate volumes for transport, and so estimates need to be made regarding how much faecal sludge accumulates over time. Therefore, samples should be collected within onsite containments, or during emptying operations. If water is added during emptying, then samples should be taken prior to the addition of water.

Designing a technology for emptying or treatment

For the design of different innovative technologies in the sanitation service chain, the steps will be similar. However, there may be specific requirements for the properties, number, frequency, and type of samples that need to be taken. For example, the design of an emptying technology may require information on waste content, viscosity, rheology, ash content, and moisture content. If this data is provided by sampling from trucks or collected at the delivery point of the faecal sludge treatment plant (FSTP), the final design of the technologies for emptying containments may not be applicable for all the containments in this particular area.

3.2.3 Treatment

Designing a new faecal sludge treatment plant

If the objective is to design a new FSTP, part of the design study will include evaluating the characteristics that will arrive at treatment, in order to specify design values. Samples should be taken at an existing FSTP. When there is not an existing FSTP then sludge is frequently dumped in locations around town. Potentially samples could be taken at illegal discharge locations, but this can be difficult to arrange with the emptiers since it is an illegal activity. Illegal dumping is an undesirable practice and the sampling from such locations is only for the purpose of improving the current situation, not to endorse it. For more information on estimating Q&Q at this scale, refer to Chapter 5.

Evaluating operational parameters during the start-up phase of a faecal sludge treatment plant

When commissioning a new FSTP, the start-up period can require months of continuous testing and optimisation to reach the required treatment performance and to optimise treatment capacity. During the ongoing operation, operators will need to adjust operations and loadings on a regular basis; for example, resting time of settling-thickening tanks, and loading rates and residence times on drying beds. Sampling needs to be appropriate for the targeted treatment processes; for example, at the inlet and on the drying beds to determine the optimal drying time on unplanted drying beds.

Monitoring overall faecal sludge treatment plant treatment efficiency

If the objective is to evaluate compliance with environmental regulations for effluent, then sampling should be consistent with the requirements of the regulations (*e.g.* effluent prior to discharge). If the objective is to evaluate overall treatment performance, then sampling should be done at the influent (*e.g.* truck discharge), and also effluent and the final treated solids.

3.2.4 End use

Assessing compliance with requirements for end use

If the objective is to assess compliance with requirements for end use or resource recovery, then

appropriate sampling should be done on the final product for the characteristics of concern (e.g. nutrients, stabilisation, calorific value, pathogens). For example, for concerns specific to use as a dry combustion fuel, see Andriessen *et al.* (2019).

3.3 REPRESENTATIVENESS

Faecal sludge varies temporally and spatially at different scales (e.g. within containment, within communities). Due to this high variability, obtaining a representative sample for volumes, properties or characteristics can be very challenging. The goal is to obtain a sample that has a similar composition to the whole substrate that is being sampled. When this is achieved, then the sample can be considered representative of the targeted faecal sludge. It is important to remember that it is highly unlikely to obtain a representative faecal sludge sample if it is taken only at one time and from one sampling point. A single sample will most likely not provide meaningful information to support the sampling objectives.

Factors to consider when determining representativeness include solid or liquid nature, homogeneity or heterogeneity, changes with time, and scale. Various types of containment technologies such as pit latrines, septic tanks, cess pits, and composting toilets will have different sampling requirements that need to be considered (see Example 5.1). If the containment or sampling location is stratified, then the level of stratification needs to be taken into account (e.g. septic tanks, wet pit latrines, stabilisation ponds). A representative sample of faecal sludge from a septic tank includes the scum, supernatant and sludge layers, which are not homogenised within the tank. These concepts are applicable to the entire faecal sludge management service chain, from collection, transport, treatment, to final end use or disposal.

3.4 SAMPLING TECHNIQUES

Once the sampling objective has been determined, the resulting sampling locations and substrates can also be identified. According to the degree of variability of the faecal sludge to be sampled, different sampling techniques are suggested.

3.4.1 Grab sampling

A grab sample, also known as a catch sample or individual sample, provides a snapshot of the current situation. This sampling technique refers to the collection of a single sample at a specific sampling location and time or over a short period of time (typically seconds or minutes). The sampling time should always be carefully determined to reduce bias and increase representativeness. Typically, grab samples are not representative of things that change with time, or a flow of heterogeneous substrates. As faecal sludge characteristics can be highly variable, care should be taken that a grab sample is representative of the whole. Discrete grab samples are taken at a selected location, depth, and time. When a source is known to be relatively constant in composition over an extended time or over substantial distances, then a grab sample may represent a larger sampling area or longer time period (Rice *et al.*, 2017). Another possibility is to use a sequence of grab samples to monitor a condition over time. Samples can then be collected at suitable intervals and analysed separately to document the extent, frequency, and duration of these variations (Rice *et al.*, 2017); for example, for typical diurnal or seasonal variations at a FSTP. Similarly, several grab samples across different locations can be used to monitor the condition of a larger space. In faecal sludge treatment processes such as inflow chambers, settling-thickening tanks, or outlet of the FSTP, samples need to be representative of the cross-section of the entire treatment unit. The samples will be individually analysed, and then they cumulatively represent a time series.

Grab samples are most appropriate for:

- Substrate with negligible changes in composition with time
- When other sampling techniques that require more resources would not provide significant improvement in terms of representativeness (see Section 3.4.2 on composite sampling)
- For small FSTPs, decentralised or semi-centralised treatment facilities with low flow and limited capacity and resources for continual sampling (however, it must be taken into account that variations can also be much greater in these cases), and

- For cases where obtaining a composite sample is not feasible because of limited access, for example from pit latrines, leach pits or septic tanks with access only through a small drop hole or access port.

3.4.2 Composite sampling

Composite samples provide a representative sampling of heterogeneous matrices in which the characteristics vary over periods of time and/or space (Rice *et al.*, 2017); for example, the flows arriving from trucks discharging at FSTPs. A composite sample can be obtained by combining portions of multiple grab samples manually over time (Rice *et al.*, 2017). Automatic sampling devices are also available for some situations, and they are often used for the sampling of wastewater in centralised, sewer-based wastewater treatment plants (WWTPs). In many cases for the sampling of faecal sludge, composite grab sampling will be the preferred method. The main advantage is analysing a composite sample instead of analysing a larger number of individual grab samples, and obtaining results that are representative of heterogeneous matrices and flows. An adequate number of grab samples is taken so that the composite is representative.

Composite samples can be prepared in different ways. Sequential (time) composite samples are made up of sub-samples of equal volume taken at specific time intervals. For example, grab samples could be sub-samples taken once an hour, which are then combined to make a single daily sample, whereas flow-proportional sampling is proportional to the flow or loading. They can be taken by mixing equal volumes of substrate collected at time intervals that are inversely proportional to the volume of flow, or by mixing volumes of substrate proportional to the flow collected at regular time intervals (Rice *et al.*, 2017). This can be done manually, or with a purpose-designed sampler. For static heterogeneous substrates, a composite can be made up from randomly taken grab samples distributed throughout the entire substrate source. It should be noted that the composite samples must be comprised of grab samples that have been collected within a short period time: between a few hours and a few days. If the grab samples have been

collected in longer time intervals such as a number of weeks or longer, they cannot be mixed as a composite sample and they need to be analysed separately as the characteristics may have changed significantly over this period. It is critical when compiling a composite sample to make a representative sample from the combination of all the grab samples collected. The aliquot of a composite sample needs to be well-mixed and effort must be made to minimise the possibility of sample contamination during the process.

Below are examples of composite grab sampling:

- In the case of sampling a sludge blanket layer in a septic tank, grab samples from multiple chambers and locations may be required to make a representative composite sample of the sludge contained in the tank (see Section 3.5.2).
- In the case of a liquid stream, equal volumes of a sample could be taken at time intervals to create a composite sample. For example, during truck discharge (taking one sample at the beginning, two in the middle, one at the end, see Section 3.5.2), or at the effluent of the FSTP. Another example of making a composite sample is to weight grab samples according to the faecal sludge loading patterns of each unit in a treatment chain at a plant.
- In the case of a completed or stabilised pile of compost as shown in Figure 3.1, a composite grab sample could be taken by grabbing samples distributed throughout the pile and then evenly mixing them into one composite sample. This is based on the assumption that stabilised compost is relatively solid, could be heterogeneous, and does not change with time.
- In the case of monitoring the dewatering of sludge on a drying bed, composite grab samples are taken from throughout the bed, for example using a grid system and taking one sample from each grid. It is important to take a core sample, and not only sample from the surface. Dewatered sludge on a drying bed is also relatively solid (depending on the level of dewatering), is probably heterogeneous, and does not change rapidly with time. A difficulty is if the sludge is not dry enough to walk on, in this case if only the edge of the drying bed can be reached, then the sample would not be as representative.



Figure 3.1 Stabilised pile of compost at the Niayes faecal sludge treatment plant in Dakar, Senegal, 2019 (photo: A. Ferré).

3.5 SAMPLING AND MEASURING DEVICES

Provided in Table 3.1 is an overview of the measuring devices that are described in this chapter, together with the measurements that they are suited for, and the advantages and disadvantages of each device. The devices are then described in more detail including how they can be used along the service chain. Sampling devices must be made of materials that will not contaminate or react with faecal sludge.

Polypropylene, polycarbonate, high-density polyethylene (HDPE), polytetrafluoroethylene (Teflon), glass, and stainless steel are relatively inert and are all appropriate for sampling. However, the cost of Teflon and stainless steel equipment might prohibit or restrict their use, and potential for breakage of glass should be considered. If using metal equipment, depending on the analysis, galvanised or zinc-coated items should not be used as these materials will release zinc into the sample.

Table 3.1 Overview of sampling devices for faecal sludge.

Sampling device	Type of measurement	Advantage	Disadvantage
L-stick sludge and scum measuring device	• Depth of containment (septic tank) • Scum and sludge depth	• Affordable • Can be self-constructed	• Lower accuracy • Requires some training • Not suitable for thicker sludge
Core sampling device	• Characterisation of more liquid sludge • Height of scum, supernatant, and sludge layers • Visualisation of the different layers	• Easy to use • Can be self-constructed	• Not suitable for thicker sludge • Needs attention to prevent leakage at the bottom of the device (e.g. due to solid waste preventing watertight closure)
Vacuum sludge sampling device	• Characterisation of more liquid sludge	• Collection of sludge at a specific depth • Able to sample thicker sludge at bottom of containment • No mixing of sludge sample with other layers	• Energy required for vacuum pump • Heavy to transport • Not necessarily available on local market • Relatively expensive
Cone-shaped sampling device	• Characterisation of thicker sludge	• Suitable for thicker sludge • Possibility to sample sludge at a specific depth	• Depending on depth and thickness, cannot sample from bottom of containment
Grab sampling device, horizontal	• Characterisation of liquid flow	• Avoids contact with sludge • Easy to use • Affordable • Can be self-constructed	• Limited use (<i>i.e.</i> specific to truck discharge, effluent samples) • Reliant on emptying operation • Not suitable for onsite containments
Grab sampling device, vertical	• Characterisation of liquid flow (treatment plant)	• Adequate for homogenous liquid stream • Allows samples to be collected in deep tanks • Can be self-constructed • Affordable	• Representativeness needs to be evaluated • Not suitable for onsite containments
Automatic composite sampler	• Characterisation of liquid flow (treatment plant)	• Consistent sampling • Effective means to collect data for daily operation at treatment plants • Time-saving • Flexible sampling programs	• Energy required • Expensive • Not always locally available • Not applicable for thick sludge
Distance-laser measuring device	• Sludge and containment depth and volume	• Greater precision and accuracy • Obtains quantitative measurement	• Cannot measure extremely large/small containment sizes
Portable penetrometer	• Shear strength of faecal sludge (related to viscosity)	• Rapid estimation of total solids (requires more testing) • No need to collect sample	• Requires trained staff • Measurement takes time • Not locally available • Requires further testing

3.5.1 L-stick sludge and scum measuring device

When sampling *in situ* from septic tanks, cess pits, and 'wet' pit latrines, it is sometimes important to consider the height or depth of the sludge layer, scum layer, and supernatant separately (refer to Example 5.1). An L-stick, shown in Figure 3.2, can be used to measure these layers; it is a long stick similar to a garden or concrete hoe.

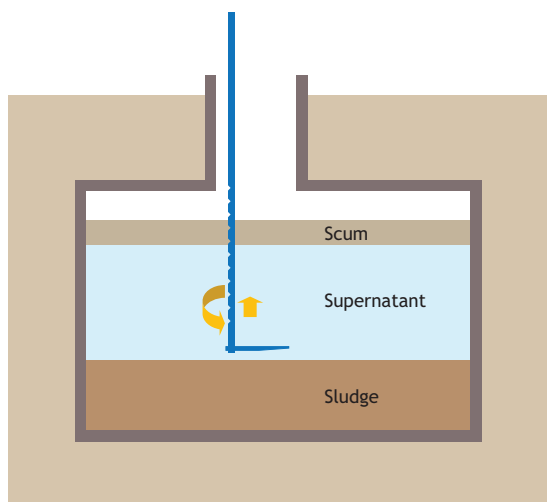


Figure 3.2 L-stick measuring device for depth of layers in a septic tank.

The stick has calibrated notches or nails to measure the depth at which it is inserted. For scum, the layer needs to be firm, with a crust, but not solid. The stick is poked through the scum, rotated 90°, and gently raised until the 'L' touches the bottom of the scum. For the sludge blanket layer, as the hoe is lowered it can be difficult to tell when the hoe first hits the sludge, and requires some practice. In some countries, L-sticks are used by emptiers to determine whether septic tanks should be emptied. The top of the sludge blanket layer is noted, and then the device is lowered to touch the bottom of the tank. One rule of thumb is that if resistance is felt from the top of the sludge blanket to halfway to the bottom, it requires emptying (Khan *et al.*, 2007). The core sampling device described in the following section is an alternative for measuring the depth of layers.

3.5.2 Core sampling device

The core sampling device shown in Figure 3.3 captures a vertical section of the substrate matrix. It is useful for sampling representative sub-samples of different layers in wet containments that have settled for many months or years, such as scum, supernatant, and thickened sludge. It can also be used to take samples from the access port of collection trucks, or tanks at treatment facilities. However, this type of sampling device is difficult to use with thicker sludge or sludge with large amounts of municipal solid waste, because it is difficult to push the device through the layers (Figure 3.3).

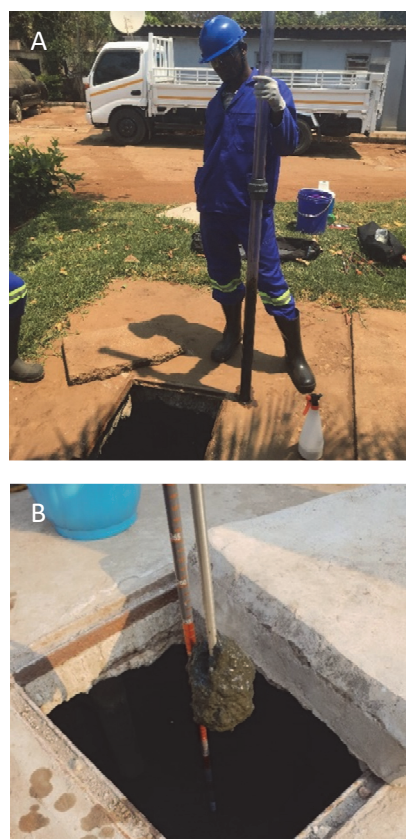


Figure 3.3 A) taking a core sample from a septic tank in Lusaka, Zambia, and B) the sampling device becomes clogged if the sludge is too thick. This example shows the collection from a 10-year old septic tank that had never been emptied. The tank was leaking, and so the supernatant leached out into the soil, resulting in a very thick sludge accumulation (photos: Eawag).

Another example of a core sampling device is shown in Figure 3.4. It consists of four transparent tubes (Figure 3.4, 1) that fit together, and four stainless steel rods (Figure 3.4, 2) that screw together inside the tubes. The device can be disassembled for transport, as well as shortened or extended as required. The tubes are graduated to measure volume. In the bottom tube the rod is attached to an airtight cover or plunger (Figure 3.4, 3) to close off the bottom of the sampler. This cover can be constructed from different materials, but it is very important that it can make a watertight seal. An alternative to the rod is a string. During sampling, the tube is inserted in the containment until the cover touches the bottom. Upon reaching the bottom, the cover should be left to settle for 30-60 seconds, allowing for any disturbed solids to settle. The hollow tube is then placed slowly over the cover, which is tightened with the string or rod (Figure 3.4, 4) to ensure a watertight seal so the sample can be removed. It is important not to make the device too large or it will be difficult to remove the sample without spilling.

3.5.3 Vacuum sludge sampling device

The vacuum sludge sampling device shown in Figure 3.5, also called a sampling hand-pump device, was developed by the Asian Institute of Technology (AIT). It was designed to take a sample at a designated depth with minimal disturbance to the surrounding layers. The device consists of a sample collection tank, a vacuum tank, and a hose. When taking a sample, the sample collection tank is evacuated, the vacuum pressure is set, and then the hose is placed in the exact location where the sample is desired. The suction valve of the vacuum tank is then released to collect the sample. The hose is brought back up, and the collected sample is released into a container by opening the discharge and air valves to normalise the pressure. This device is suitable for sampling from onsite containments and treatment technologies, to collect a sample at a specific depth.



Figure 3.4 Graduated core-sampling device developed by CDD, India (Prasad et al., submitted, photos: CDD, India).

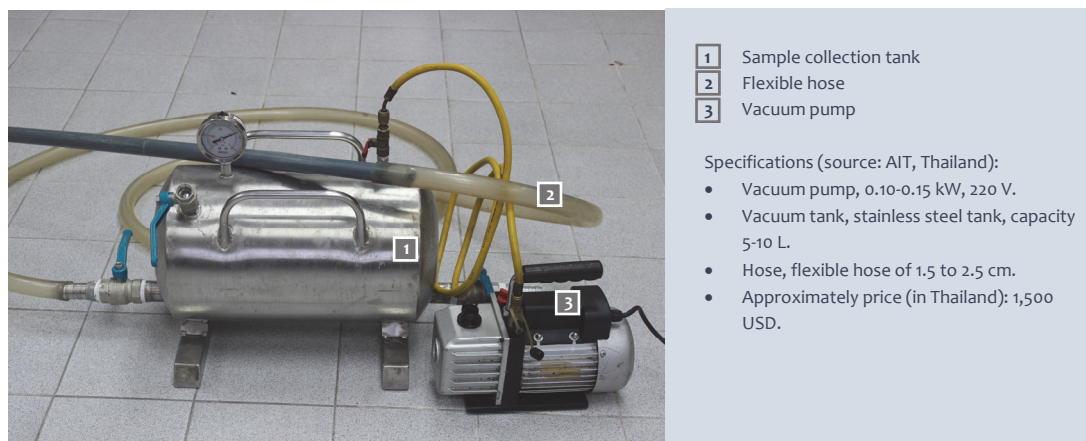


Figure 3.5 Vacuum sludge sampling device (photo: AIT).

3.5.4 Cone-shaped sampling device

The cone-shaped sludge sampling device shown in Figure 3.6 can be used to collect samples in relatively 'dry' or less liquid onsite containments. Samples can be taken at a specific depth through a controlled valve that opens to take the sample, and closes to bring the sample out. Solid waste in containments complicates the operation and obtaining a representative sample due to clogging. The cone-shaped sampler in Figure 3.6 is 3 meters high with hinged arms, to allow for sampling of onsite containments within super-structures. The sample size is approximately 1 L.

Similar devices have been used in many locations in sub-Saharan Africa, including the University of Zambia (Tembo, 2019), Makerere University (Zziwa, 2019), Egerton University (Muchiri 2019), and Jimma University (Beyene *et al.*, 2019). Modifications include a hinged opening and closing instead of a valve operation. Production of one unit in sub-Saharan Africa is around 300 USD in Kenya and Zambia. An example of sampling in Lusaka is provided in Case study 3.1.

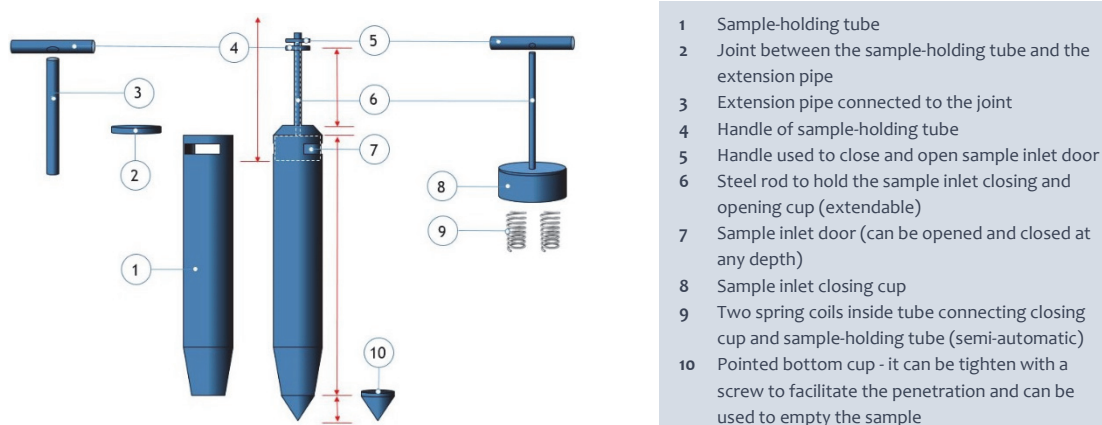


Figure 3.6a Schematic of the cone-shaped pit-sampling device.



Figure 3.6b Cone-shaped pit-sampling device in use in a study in Ethiopia (photo: Beyene *et al.*, 2019).

3.5.5 Grab sampling device - horizontal

The grab sampling device shown in Figure 3.7 consists of a sampling container of a known volume mounted on the end of a bar or rod.



Figure 3.7 A grab sampling device used for sample collection during truck discharge in Kampala, Uganda (photo: Eawag).

This sampling device is suitable for collecting faecal sludge at the discharge valve of the vacuum truck, as well as in some locations in treatment facilities (e.g. an FSTP outlet pipe). The sampling container is usually made of rigid plastic or stainless steel with a wide opening and a spout for emptying the sample. The bar or rod needs to be strong enough to avoid deformation or breaking during the sampling, because the flow from the outlet of the vacuum truck can be quite strong, and also long enough to protect the person collecting the sample from being splashed by sludge. The device allows for samples of a known volume of faecal sludge to be taken at a point in time. The sampling container is typically 1 L.

3.5.6 Grab sampling beaker device - vertical

The sampling device shown in Figure 3.8 is similar to the one shown in Figure 3.7, but the sampling container is oriented for samples to be taken vertically at depth of relatively homogenous substrates, such as supernatant in a settling tank. The length of the rod is dependent on the depth at which samples are taken. The sampling container should have a flat bottom, and the rod should be slightly flexible.

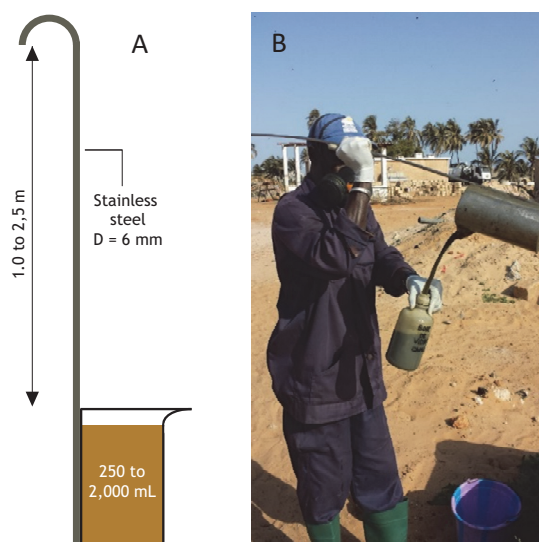


Figure 3.8a A) schematic of the grab sampling beaker device. B) at the outlet of the Cambérène FSTP, ONAS staff, Dakar, Senegal. Note: wide-mouth containers are preferable for sample allocation, as they aid sample collection without spillage (photo: Eawag).



Figure 3.8b Use of the sampling device in the liquid stream at the treatment plant (photo: IHE Delft).

3.5.7 Automatic composite sampler

Automatic composite samplers as shown in Figure 3.9 are commonly used in WWTPs, and can also be used for sampling the effluent of FSTPs. The system requires energy and is equipped with a peristaltic pump. A composite sampler usually includes several modes and sampling methods such as composite sampling (multiple samples are combined in a single large container), or sequential distribution (multiple samples are taken and stored in multiple bottles). Sample interval and time need to be selected, and can be uniform (commonly once an hour for 24 hours), or non-uniform.



Figure 3.9 An automatic composite sampling device (photo: IHE Delft).

Multiple samples are necessary when samples larger than 1,000 mL are required for analysis. As explained in Section 3.4.2, composite samples can be taken as fixed volume or flow proportional. Composite samplers include refrigeration for sample preservation. Single-bottle composite sampling is commonly used for influents and effluents, while multiple-bottle sampling is used to identify operational issues in treatment technologies.

3.5.8 Distance laser measuring device

The Volaser (*volume laser*) measuring device shown in Figure 3.10 is being developed by Eawag for measuring *in-situ* volumes of accumulated faecal sludge and volumes of containments (Andriessen and Strande, in preparation). The Volaser can be used to estimate accumulation rates as presented in Chapter 5 and Case study 3.1. The Volaser consists of a distance laser measuring unit, a tripod stand, and a probe to measure depth. The tripod is set up over a vertical access port to a containment. The laser unit is then lowered into the containment, and rotated as it measures the distance to the walls of the containment. Afterwards, the same laser unit is used to measure the distance from the top of the containment to the faecal sludge surface. A collapsible metal probe that is 3 m long is used to physically determine the depth of the containment. These measurements, along with the GPS coordinates, are recorded in a smartphone app which then automatically calculates the required volumes. The measurements take on average less than ten minutes with an accuracy of <10% error (e.g. ± 0.2 for a 2 m³ containment). The Volaser device is not applicable for extreme cases (e.g. depth greater than 3m, access ports at an angle, or extremely large storage tanks). The Volaser can be operated by one person, and works well with a team of 2-3 people if sampling also includes characterisation and questionnaires. A version that can be locally assembled for less than 350 USD is expected by 2021 (Andriessen and Strande, in preparation). The tool can be adapted to local needs, and is applicable for all types of onsite containment technologies. Previous attempts at *in-situ* measuring devices include a laser measuring device to measure the 3D surface of sludge in pit latrines; however, further development is required due to light interference (Dahmani, 2010).



Figure 3.10 A) schematic of the Volaser with a laser measuring head that enters the containment to measure the area and distance to the sludge, with a smartphone mounted on top. Photos are from Lusaka, Zambia of (B) the prototype version used in 2019, with the Volaser placed over an access to a pit latrine (C) (photos: Eawag).

3.5.9 Portable penetrometer

The portable penetrometer shown in Figure 3.11 is intended as a relatively simple and quick *in-situ* test for shear strength of faecal sludge (related to viscosity) (Radford and Sugden, 2014). The penetrometer gives a continuous profile of how sludge

varies throughout the depth of a containment. The device still requires further development, but the goal is to predict TS based on the *in-situ* penetrometer measurements, for rapid estimates at community to citywide scales. One measurement takes approximately twenty minutes with a skilled team of two to three operators.



Figure 3.11 A and B) the portable penetrometer in use in Kampala, Uganda; C) the new 'P-lite' model for easier mobility in the field which is under development (photos: J. Radford).

3.6 SAMPLING METHODS AND LOCATION

Once the sampling objective has been determined, sampling locations in the faecal sludge management service chain and the sampling methods and devices can be selected. There are specific concerns for each step in the faecal sludge management service chain, including type and usage of onsite containment, collection and transport, type of treatment processes, and final end use or disposal. The reality is that obtaining representative sampling from containments can be difficult, as they are closed, underground systems, and samples cannot always be taken exactly where preferred. When selecting the sampling location, if the preferred location is not possible, then the closest representative alternative should be selected. The decision process should be documented, and evaluated for bias. For example, if the objective is to determine *in-situ* total loadings of accumulated faecal sludge, and sampling takes place during discharge at treatment plants, it will not necessarily be reflective of the total accumulated sludge if containments are not fully emptied. Another example is if sampling can only be done when they are full and require emptying (Strande *et al.*, 2018), because as illustrated in Figure 3.12, accumulation rates of total volumes of faecal sludge in containment do not accumulate linearly due to biological, physical and chemical properties (see Chapter 5). What triggers the emptying event is typically a nuisance event such as backing up or overflowing.

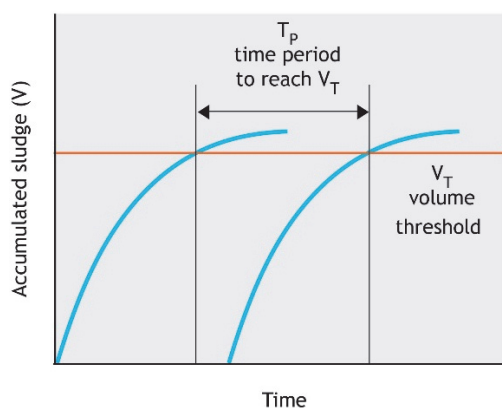


Figure 3.12 The blue lines illustrate change in the faecal sludge accumulation rate and T_p is the amount of time to reach V_T , the volume threshold where emptying is triggered.

The reality is that sampling will be dependent on the available resources. Assumptions will have to be made when designing a sampling campaign, which can be validated during implementation from different sampling locations. This is further discussed in Case Study 3.3 and Chapter 5. The following section presents examples of sampling along the service chain.

3.6.1 Sampling *in situ* from onsite containment technologies

In Chapter 2, faecal sludge is classified as liquid (total solids content <5%), a 'pumpable' slurry (total solids 5-15%), a 'spadable' semi-solid (total solids 15-25%), or a 'solid' (total solids >25%). Sampling methods are classified for more 'wet' or 'dry' faecal sludge, but in reality, in many systems or locations the faecal sludge will be a combination of types, and what is most appropriate for each situation will be context-specific, as illustrated in Case study 3.1.

In-situ sampling of a wet toilet system (faecal sludge < 5% TS)

This category can include many types of containment, including pit latrines or septic tanks, lined, unlined, or partially lined, one or multiple chambers, with or without overflows, and with soakaways or drain fields. The sampling location depends on the objective, and also on accessibility (Figure 3.14).



Figure 3.13 A septic tank located below a house, requiring the floor to be broken for emptying or sampling, Hanoi, Vietnam (photo: Eawag).

Sampling from septic tanks can be done via access ports, but they are also frequently sealed, covered over, or even located under buildings, as shown in Figure 3.13. In the latter case it can be difficult to know which part of the septic tank is being sampled.

Samples are frequently collected as core samples to collect a representative sample of all accumulated sludge layers. Grab samples of the effluent from the septic tank can also be collected to evaluate settling

performance/solids removal. Examples of sampling locations in a two-chamber septic tank are provided in Figure 3.14. According to the sampling objective and strategy, a composite sample may be made from core samples from the different chambers of the wet toilet system or from grab samples collected at regular time intervals. Sampling could be also done directly through the toilet access hole in ‘wet’ pit latrines. In other cases, the depth of the sludge layer, supernatant, and scum layer can be measured with an L-stick.

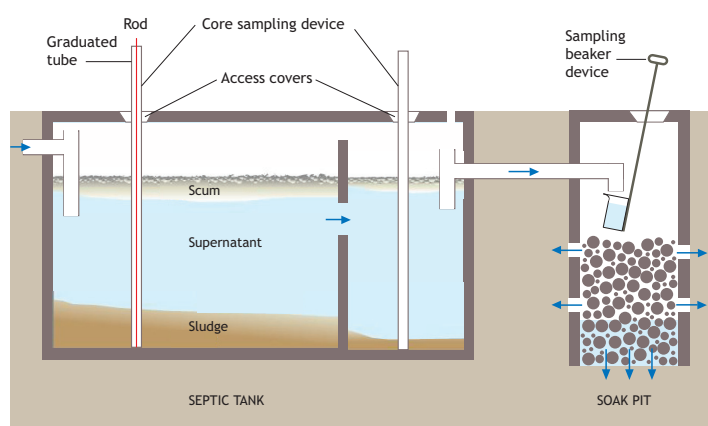


Figure 3.14 Sampling points in a septic tank: on the left is a vertical core sample in the first chamber, in the middle is a vertical core sample in the second chamber and on the right is a grab sample of the septic tank effluent (depending on configuration, e.g. a distribution box or open drain).

In-situ sampling of dry containments (faecal sludge > 15% TS)

In-situ sampling of dry containments for characterisation can be done with the cone-shaped sampling device (Section 3.5.4) through the toilet access hole. Sludge volumes and depths can be measured with the Volaser measuring device (Section 3.5.8). Examples of *in situ* sampling are found in Case Study 3.1.

Case study 3.1 *In-situ sampling to estimate quantities and qualities (Q&Q) of faecal sludge in Lusaka, Zambia*

Eawag and UNZA conducted a study from September to December 2019 in Lusaka, Zambia to estimate quantities and qualities (Q&Q) of faecal sludge,

specifically characteristics and accumulation rates (see Chapter 5). 82% of Lusaka relies on onsite sanitation, with 55-70% being pit latrines and 10-20% septic tanks (GFA Consulting Group GmbH, 2018). Observed total solids concentrations of 420 collected faecal sludge samples ranged from 0.1 to 40% measured gravimetrically, illustrating the wide range of characteristics that are present. To account for this diversity, different sampling devices were needed for *in-situ* sampling from septic tanks and pit latrines. For the design of the sampling plan see Case study 5.1.

Upon arrival at the sampling site, the containment was inspected to see if it could be sampled. A collapsible metal probe (3 m length) was used to measure the depth of the containment. For pit latrines, a cone-shaped sampler with a hinged arm was used to

collect samples, as shown in Figure 3.15. Faecal sludge up to 40% total solids could be sampled with the cone-shaped sampler, and the minimum required sludge for sampling was 50 cm. The pit latrine samples were collected directly through the opening in the toilet. A core sampling device was used for

septic tanks (Figure 3.15). The core sampler was graduated, to simultaneously measure the depth of the total sludge level and the sludge blanket layer. Faecal sludge from septic tanks was sampled in the first chamber of the tank. The cone-shaped sampler and the core sampler were both 3 m long.



Figure 3.15 A) a core sampling device, B and C) a cone-shaped sampler, D) the Volaser measuring device (photos: Eawag).

To measure the total volume of the containment, the Volaser measuring device was used (Ward *et al.*, 2021). The measurement was started through the smartphone app, and the Volaser was rotated while the laser was measuring the distance to the walls, angle of rotation, and calculating the area of the containment (Figure 3.10). The distance to the sludge surface was also measured. Based on collected data including time since last emptied, it was possible to estimate the sludge accumulation rates.

Samples collected for characterisation were poured into a bucket, stirred for homogenisation, and 0.9 L was transferred to a plastic container. Samples were stored in a cooler box with ice packs during transportation and delivered to the laboratory at the end of the sampling day, where they were immediately stored in a refrigerator. Analysis included TS, VS, COD, electrical conductivity, pH, NH₄-N, capillary suction time (CST), colour, odour, foam and C/N ratio. Duplicate sampling was conducted every 5 samples and triplicate sampling every 20 samples to test the replicability of the sampling method. Following this procedure, 6-7 samples could be collected per sampling team in one day. ■

3.6.2 Sampling during emptying of onsite containment technologies

As discussed, *in-situ* sampling is often not possible, and so sampling is frequently conducted during emptying operations.

Sampling of dry toilet containment during manual emptying

Manual emptying occurs with all types of faecal sludge in areas where vacuum trucks cannot access due to narrow lanes or paths, where faecal sludge is too thick for vacuum pumps, or where vacuum trucks are not available. Faecal sludge is commonly emptied into barrels, which can then be transported by cart or small trucks to a treatment plant or transfer station. Figure 3.16 shows examples of manual emptying operations in Lusaka, Zambia, and in Durban, South Africa. If the sampling objective is to determine average characteristics, grab samples could be taken from the barrels, and combined into a composite sample. Examples of dry toilet systems are urine

diverting dry toilets (UDDT) and dry pit latrines with total solids > 15%.



Figure 3.16 A) sampling during a manual emptying operation in Lusaka, Zambia, and B) Durban, South Africa (photos: Eawag).

If the sampling objective is to evaluate how sludge degrades over time and with depth inside a pit latrine, samples can be taken from different vertical layers during emptying. Buckley *et al.* (2008) propose that faecal sludge in dry toilet systems can be classified in

four layers as: (i) fresh stools, (ii) a partially degraded aerobic surface layer, (iii) a partially degraded anaerobic layer beneath the surface, and (iv) a completely stabilised anaerobic layer. Velkushanova (2019) and Zuma *et al.* (2015) developed their sampling methodology based on Buckley *et al.* (2008) and proposed that a dry toilet system can be further divided into two sub-sections: a back section and a front section (under the pedestal) as presented in Case study 3.2. Faecal sludge sampling should be done at different depths at the front and back of the pit, as containment of sludge in dry ventilated improved pit (VIP) latrines is not evenly distributed. In contrast to wetter sludges, it is possible to have a higher heap of sludge accumulate directly underneath the pedestal. Similarly, faecal sludge samples can be selected from both active and standing vaults of the UDDT toilets and other dry containment systems, outlined in Case study 3.2. These separations or distinctions should be considered during sampling to ensure an overall representative sample of the entire containment system, and are represented by the numbers in Figure 3.17.

Case study 3.2 Sampling methods and locations of different dry onsite sanitation systems in Durban

The Pollution Research Group at the University of KwaZulu-Natal (UKZN PRG), South Africa carried out a study into the properties of faecal sludge from onsite sanitation facilities in the Durban metro area, including: wet and dry household VIP latrines, household UDDTs, household unimproved pit latrines, community ablution block (CAB) VIP latrines, and school VIP toilet blocks. The goals were to provide a better understanding of the potential use of faecal sludge as a biofuel or fertiliser, to support the design and sizing of mechanical pit-emptying devices, transportation and processing systems for the excavated sludge, and the design of future onsite sanitation facilities. The study took place during 2012 and 2013.

Pit emptying

The first phase of the project involved a sampling program (Table 3.2) to obtain faecal sludge samples from selected onsite sanitation facilities in peri-urban and rural areas of Durban that are serviced by the eThekweni Municipality.

Table 3.2 Distribution of 45 samples in peri-urban and rural areas of Durban.

Facility type	Characteristics	Usage level	Number of onsite sanitation systems sampled	Location
Household VIP latrine	Dry	Low usage (<5 users/onsite system)	5	Besters
		High usage (>5 users/onsite system)	5	
	Wet	Low usage	5	Besters
		High usage	5	
Household UDDT toilet		Low usage	5	Mzinyathi
		High usage	5	
Household unimproved pit latrine	Dry	Low to high usage	2	Ocean Drive
Community ablution block VIP	Dry	High usage	9	Malacca Road
School VIP toilet block	Wet and dry	High usage	4	Mzinyathi
Total			45	

Sludge sampling

The faecal sludge in pit latrines varies widely, which makes the comparison between samples collected from the different onsite sanitation facilities challenging. In order to provide a uniform data comparison, a sampling method was developed and applied for selection of samples from different depth levels at the front and back of the pit for all dry VIPs (Figure 3.17, top left). Sample 1 represents a fresh

deposit and is usually right beneath the pedestal, sample 5 is partially degraded aerobic faecal sludge but some of the fresh material may have fallen there, samples 2 and 6 are partially degraded aerobic faecal sludge, samples 3 and 7 are partially degraded anaerobic faecal sludge, and samples 4 and 8 are at the bottom of the containment and are completely stabilised and anaerobic faecal sludge.

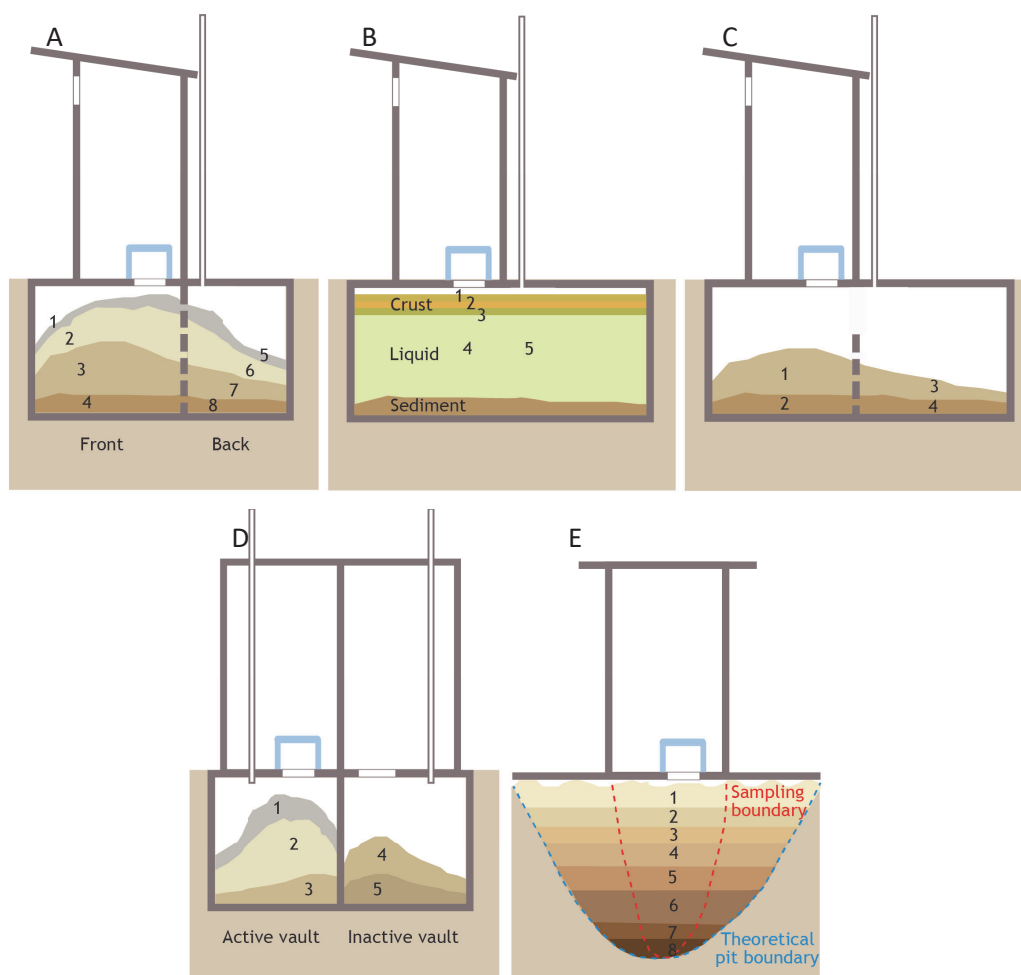


Figure 3.17 The selection of faecal sludge analytical samples used in Case study 3.1 is from: A) dry ventilated improved pit latrines (VIPs), B) wet VIPs, C) school VIPs, D) UDDT toilets, and E) unimproved pit latrines. The numbers illustrate where samples were taken.

A similar approach was followed for the UDDT toilets, where samples were selected from both active and standing vaults (Figure 3.17, bottom left). For the wet VIPs, samples were selected from the sludge crust concentrated at the top of the pit and from the liquid beneath the sludge layer but no distinction was made between the front and the back of the pit (Figure 3.17, top middle). The community ablution block VIPs did not allow for structured sampling, because of the limited accessibility for pit emptiers due to the large size of the containments and large amounts of solid waste. Samples were selected from the top sludge layer and the liquid beneath, similarly to the wet household VIPs. For the school VIP toilets, the sampling procedure was similar to the one followed for dry VIPs. Due to the shallower sludge layers, only four samples were selected from each pit (two from the front and two from the back (Figure 3.17, top right), except for one where six samples were selected

in total. For the unimproved pit latrines, seven to eight samples per pit were selected as indicated in Figure 3.17 (bottom right). This procedure was followed as there was no superstructure as for the VIP toilets, hence there were no clear boundaries between the faecal sludge disposed in the pit and the surrounding soil.

On average, eight samples were selected from each dry VIP, between four and six samples from each wet VIP, two to six from each UDDT toilet, two from each CAB VIP, four from each school toilet VIP, and eight samples from each unimproved pit latrine over a period of 18 months, where 211 samples were collected in total. The selected samples had a capacity of approximately 1 litre and were stored in plastic containers at 4°C in a cold room in the UKZN PRG laboratory for further analytical tests.



Figure 3.18 Photographs of faecal sludge samples in Case study 3.2 taken from: A) a dry ventilated improved pit latrine (VIP), B) a wet VIP, C and F) a school VIP, D) a UDDT toilet, and E) an unimproved pit latrine (photos: UKZN PRG).

Sampling from collection and transport vehicles

Sampling from collection and transport trucks is another possibility, and fits the sampling objective of knowing what will be delivered to treatment. Depending on the type of truck, samples can be taken directly from the access port on the top of the truck tank or during discharge from the discharge valve (Bassan *et al.*, 2016). In the first option a core sampling device can be used, while in the second option a composite of grab samples is collected (Figure 3.19).



Figure 3.19 A) collecting grab samples from the truck discharge valve to make a composite sample, and B) collecting a core sample from a truck access port with a 180 cm length PVC core sampling device with a 5 cm internal diameter, Hanoi, Vietnam (photos: Eawag).

The composite sample usually consists of taking one sample at the beginning of discharge, two in the middle, and one at the end (Bassan *et al.*, 2013). When possible, a volume gauge on the back of the truck can be used measure volumes, and to determine when to

take samples. Samples should be collected from the truck immediately after emptying, or from the discharge valve immediately upon arrival at the discharge facility. If trucks are left standing for even a short period of time, solids will rapidly start to settle out in the tank. A comparison of sampling methods is provided in Case study 3.3.

Case study 3.3 Comparison of four sampling methods in Hanoi, Vietnam

This case study is based on a Master's thesis by Amédée Ferré (2014), a collaborative project between Eawag and the Institute of Environmental Science and Engineering at Hanoi University of Civil Engineering. Sampling methods were evaluated during a characterisation study that took place between September 2013 and June 2014. More than 90% of households in Hanoi have septic tanks, with the overflow going directly to rainwater drains or sewer systems. Samples were taken from six different septic tanks with the number of chambers varying from two to three, and for each of the six septic tanks four different sampling locations were compared. Core samples were taken with a 1.8 m high PVC core sampler with an internal diameter of 5 cm. Grab samples were taken with a 1 L grab sampling device (bucket mounted on the end of a 1 m long bar).

1. Septic tank: samples were taken *in situ* from septic tanks with a core sampling device. This included from the bottom to the liquid surface (*i.e.* a core sample of sludge layer, supernatant and scum layers). However, the specific location in the septic tank where the sampling occurred could not be identified.
2. Truck access port: samples were taken with a core sampling device *in situ* from the access port on the top of the vacuum trucks, immediately following collection of septic tank sludge from households.
3. Beginning discharge: a single grab sample of 2 L taken from the truck valve at the beginning of the discharge.
4. Composite discharge: a composite sample comprised of four grab samples of 1 L each, taken from the truck valve at the beginning, middle and end of the discharge in a ratio of 1:2:1.

Presented in Figure 3.20 is a comparison of the TS and COD results for each of the sampling methods. The results illustrate the importance of sampling location depending on the objective and evaluating bias. The septic tank is more relevant if the objective is to determine sludge accumulation rates in the septic tank, whereas either the truck access port or the composite discharge is preferable for constituents of faecal sludge being delivered to treatment. In the case of thick faecal sludge (septic tanks 1 and 3), the composite discharge may be more representative than the truck access port, whereas for more liquid sludge (e.g. septic tank 6) the truck access port may be more suitable (*i.e.* larger supernatant volume). The

beginning discharge appears to be biased to solids that settle out in the truck, and are washed out at the beginning of discharge (e.g. septic tanks 1, 2 and 3). Further analysis is needed to fully understand the effect of sampling location. Samples were taken from trucks, as service providers were reticent to allow sampling during discharge. There is no legal discharge location in Hanoi, and sampling would draw attention to their illegal discharge (although the businesses are legally registered). Samples were also analysed for total suspended solids (TSS), nutrients, volatile fatty acids (VFA), and proteins, and the raw data is available for download using the link provided in Englund *et al.* (2020).

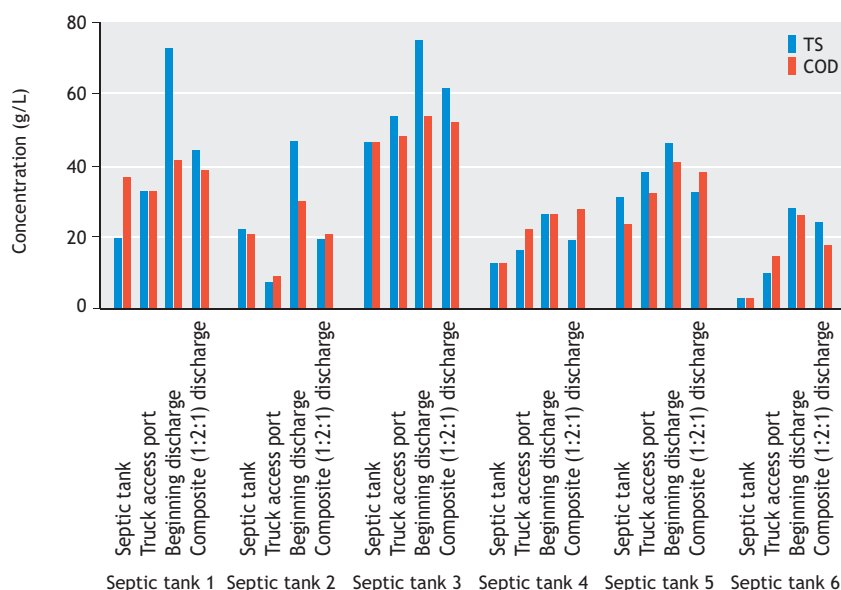


Figure 3.20 Total solids (TS) and organic matter (COD) results for six septic tank samples that were collected with four different methods.

3.6.3 Sampling at faecal sludge treatment plants

FSTPs can have combinations of various technologies such as settling-thickening tanks, drying beds, waste stabilisation ponds, and mechanical dewatering. Sampling locations and strategies will depend on the objective, for example, treatment performance, operational concerns, monitoring, resource recovery, and optimisation of loadings. In general, liquid and

solid streams require different approaches to collection and analysis. For the sampling of liquid streams with similar characteristics to wastewater, refer to Meijer and Brdjanovic (2012), and the USEPA operating procedure for wastewater sampling (2017). Below are two examples of sampling at FSTPs; more information on dewatering and drying is available in Chapter 4 and Ward *et al.* (2019).

Case study 3.4 Assessing FSTP performance

A hypothetical FSTP in South East Asia consists of two settling tanks in parallel, planted drying beds, and vertical flow constructed wetlands. The effluent is discharged by gravity into a river. The FSTP opening

hours are from 8 am to 6 pm on Monday to Saturday. The FSTP operator has defined the sampling objectives as evaluating the FSTP performance to assess future investment needs, and defined the sampling plan summarised in Table 3.3.

Table 3.3 Sampling plan to evaluate a FSTP performance in South East Asia.

Item	Sampling plan	Observation
Sampling location	- Discharge channel right after screening (laminar flow). - Manhole at the outlet of the vertical flow constructed wetlands.	Flow and turbulence are high in the channel before screening.
Sampling technique	- Composite of 6 grab samples of equal volume taken every 2 hours. - Grab samples.	- Single daily composite. Due to limited human resources and time, interval time between 2 sampling is set at 2 hours (ideally every hour). - The outlet flow composition is assumed to be constant.
Sampling equipment	- Grab sampling device, vertical, 1 L volume with a 1 m rod to collect samples at half depth of the sludge flow in the discharge channel. - Grab sampling device, vertical, with 2 L volume and 3 m rod to access the bottom of the manhole.	- Sampling devices and containers were first rinsed 3 times with the targeted substrates (<i>i.e.</i> untreated faecal sludge or effluent). - The beaker is lowered to a depth of around 50 cm into the channel and then inclined to face the flow. It is assumed that the collected sample is representative of the flow.
Storage containers	6 x 500 mL PTFE plastic containers. 2 x 2 L PTFE plastic containers. 2 x 250 mL sterilised glass containers.	- Sterilised glass containers for further microbiological analyses. - First rinsed 3 times with the targeted substrates (<i>i.e.</i> untreated faecal sludge or effluent).
Sample preservation technique	- The six grab samples are immediately stored in a cool box with ice. - The effluent grab sample is transported to the lab in a cool box together with the two glass containers.	Since microbiological parameters must be analysed within 6 hours, a single grab sample is taken specifically for these parameters.
Protective equipment	Rubber boots, protective gown, protective glasses, active carbon filter mask, and rubber gloves.	

Case study 3.5 Planning for measures to reduce exposure to contamination risk

A hypothetical FSTP in West Africa consists of unplanted drying beds, each equipped with a discharge channel with a screening grid, a buffering storage tank for treated effluent reuse and a dried sludge storage area. The effluent, if not used, is infiltrated. After being removed from the drying beds, sludge is stored for one year (Figure 3.2.1). The FSTP operator has defined the sampling objective of evaluating compliance of dried sludge with agriculture reuse requirements to reduce farmers' exposure to faecal contamination risk. In order to fulfil this objective, the FSTP operator will assess the pathogen content of the dried and stored sludge, as described in Table 3.4.



Figure 3.21 Dried sludge at a faecal sludge treatment plant in West Africa (photo: A. Ferré).

Table 3.4 Sampling plan to evaluate the compliance of dried sludge with agricultural reuse requirements in West Africa.

Item	Sampling plan	Observation
Sampling objective	• Verify compliance of dried sludge with agricultural reuse requirements	• To reduce farmers' exposure to faecal contamination risk.
Sampling location	• Storage area: stabilised sludge after 1 year of storage	• See example in Figure 3.21
Sampling technique	• Composite of five random single grab samples distributed throughout the stabilised sludge pile.	• Stabilised sludge composition may vary throughout the pile.
Sampling equipment	• Grab device: tongs, spoon, gloves, etc depending on size	• Stabilised sludge is relatively inert, reaction with a plastic container has low probability.
Storage containers	• 1 L PVC container with wide opening	
Composite	• The sub-grab samples will be gently crushed in a mortar and the resulting powder will be mixed.	
Sample preservation technique	• The sample will be transported to the soil laboratory in a cool box with ice.	• No preservative required for microbiological parameters.
Protective equipment	• Rubber boots, protective gown, rubber gloves.	• Risk of ingestion is low.

3.7 SAMPLE SIZE

Guidelines on how to develop sampling and analytical plans taking into account the adequate number of duplicate samples to ensure accuracy and precision are presented in Chapter 8. A detailed plan for quality

assurance and quality control (QA/QC) needs to be developed in advance of sampling to take into account the increased number of samples for duplicates and controls. In reality, there are no hard and fast guidelines for determining the 'right' number of samples, and frequently the selected sample number

will come down to available time and resources. Even with a limited number of samples, by taking them in a logical fashion with defined objectives and QA/QC procedures in place, the results will still be more meaningful than if collected without these controls in place. In Example 3.1 are sample sizes based on a normal distribution. However, as presented in Chapter 1, faecal sludge does not follow a normal distribution and a statistically valid number of samples cannot be determined until a distribution is known. This means that in reality, the samples actually have to be taken before these assumptions can be validated. It is important to keep in mind that with more samples there is increased accuracy, but the increase is not linear. How to calculate the effect of sample size on uncertainty is discussed in Chapter 5, along with further information and examples of developing sampling plans for community to citywide scales, and statistical relationships that can be used to reduce the required time and resources for analysis.

Example 3.1 Sample sizes for normal distributions

If the probability distribution of a sampling population is known, equations exist to determine a statistically significant number of random and independent samples. The number of samples will depend on the selected confidence interval (margin of error) and confidence level. For example, as shown in the table for a normal distribution, if a city has a population of 2,000,000, served by 70% onsite sanitation with an average of 10 users per containment, this would mean 140,000 onsite containments. Based on the values in Table 3.5 with a 90% confidence interval and 5% margin of error, this would mean 270 samples. However, Q&Q of faecal sludge will probably not follow a normal distribution, and a much lower number of samples could logically be selected with a transparent explanation of how the number and type of samples were selected.

Table 3.5 Required sample size to fulfil a confidence interval of 90% and 95% with a margin of error of 5% and 2% for normally distributed data.

Population	Confidence interval = 90%		Confidence interval = 95%	
	Margin of error		Margin of error	
	5%	2%	5%	2%
100	74	95	80	97
200	115	179	132	185
500	176	386	217	414
1,000	213	629	278	706
10,000	264	1,447	370	1,936
100,000	270	1,663	383	2,345
1,000,000	271	1,689	384	2,396
2,000,000	271	1,690	385	2,398

3.8 HEALTH AND SAFETY

It is important to have a health and safety plan in place for sample collection and transport. Personal protective equipment (PPE), as shown in Figure 3.22, must be worn to ensure protection from pathogens and other potentially harmful constituents in faecal sludge, including appropriate handling and cleaning of contaminated clothing. Other safety considerations include working in confined and dangerous spaces, toxic gasses that build up during anaerobic digestion

of faecal sludge, water, and electricity, and moving components at FSTPs. The sampling area must also be kept clean to protect the general population from risk of exposure to faecal contamination. Any faecal sludge that is spilled during sampling must be immediately cleaned, and waste matter properly disposed of. For more information, refer to Chapter 8, and for a detailed overview of recommendations, refer to Health, Safety and Dignity of Sanitation Workers An Initial Assessment (World Bank 2019), and for hygiene practices to Louton *et al.* (2018).



Figure 3.22 Personal protective equipment. A) transferring homogenised samples to sample containers with a plastic funnel and ground protection. B) a mask and meter/alarm for H_2S . C) collecting samples from pit latrines (photos: Eawag, M. Henze, UKZN PRG, respectively).

3.9 SAMPLE COLLECTION

Prior to sampling, arrangements need to be made with the laboratory carrying out the analysis regarding sample volume and laboratory capacity. It is important to consider transportation times, working hours, weekends, and available staff. The minimum required

sample volume needs to be determined based on the number and type of analytical procedures to be carried out. An example of calculating the required volume based on planned analysis is presented in Figure 3.23. Extra sample volume should be added to account for potential spillage and other unforeseen needs during processing.

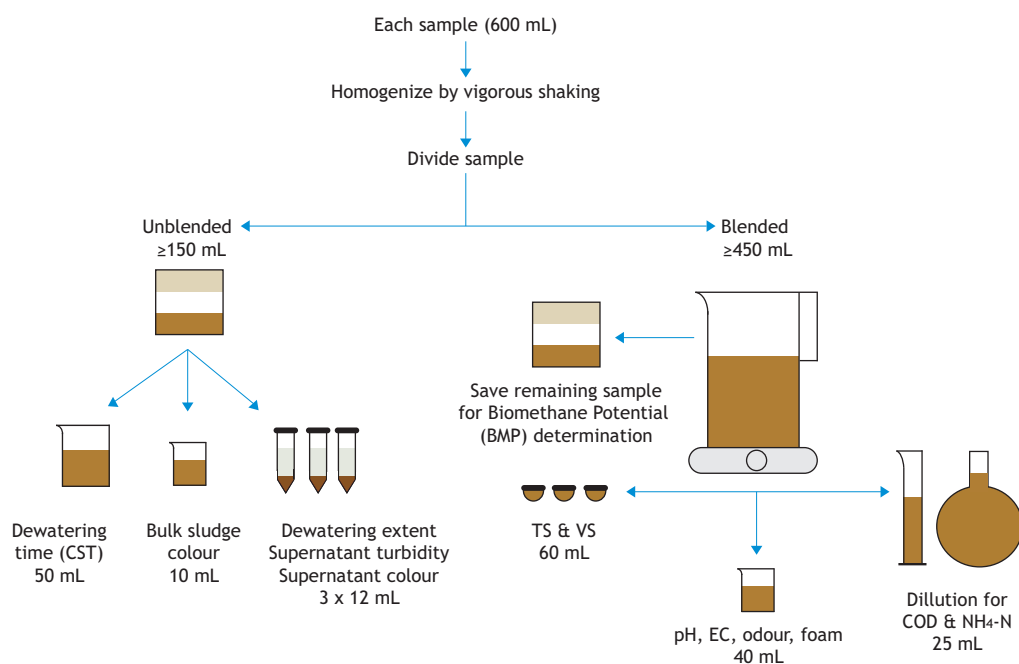


Figure 3.23 Example of how to calculate the required sample volume based on the planned laboratory analyses.

When samples will be sub-divided the sample must be homogenised. This can be done by stirring rapidly with a ladle to get all the particles in suspension and then immediately distributing to sub-sample containers. Whichever method is used, it is important to record the method, and to evaluate the accuracy and replicability. Wide-mouth sampling containers are preferred, and the use of a funnel is recommended for transfer of samples.

If making a time-related composite, all the grab samples must be stored at 4 °C until the entire sampling process is completed. If a refrigerator is not available at the sampling site, then samples should be stored in a cooler box with ice packs. In this case the composite is often prepared at the laboratory.

All the containers used to store the samples should be labelled prior to sample collection to prevent sample misidentification. Labels must be water resistant, and include at a minimum a unique sample number or code, the sampling date, nature of the sample for health and safety, and name of the laboratory where the samples will be delivered. All the sampling equipment and material has to be cleaned immediately after sampling to avoid contamination of future samples and ensure the health and safety of workers.

Equipment used to collect samples should be cleaned in the field with water and detergent. Detergent should be a standard brand of phosphate-free laboratory detergent. Under extenuating circumstances where cleaning in the field is not feasible, equipment can be containerised, bagged or sealed and cleaned upon return to the laboratory. Sampling containers must be properly cleaned prior to use or reuse and, if needed, sterilised in an autoclave. For more information on the specific procedures, methods and considerations to be used and observed when cleaning and decontaminating sampling equipment during the course of field investigations, the reader is referred to USEPA (2015).

3.10 RECORDING OF SAMPLE COLLECTION

Details on each sampling event need to be documented in a logbook immediately at the time of sampling. This documentation is useful for troubleshooting if the laboratory results are atypical or suspect; it serves to demonstrate that the proper sampling protocols were used, and is useful to interpret and compare analytical results. It is good practice to record sufficient information that the sampling procedure can be reconstructed from the logbook alone. Recorded information should include at a minimum:

- sample identification code (specific to sampling event *i.e.* type, location, date, treatment process and condition, etc.)
- number of samples and volume of sample taken,
- type of sample (*e.g.* grab, 24-hour composite), sampling equipment and a brief description of sampling procedures
- volume of sample
- date and time
- sample location, GPS coordinates
- preservatives
- analytical parameters
- name of person who performed the sampling or measurement
- special conditions or remarks, *i.e.* weather conditions at the time of sampling and other observations which could potentially impact the laboratory analytical results
- brief description of the sludge collected, *e.g.* colour, odour, viscosity, consistency.

A chain-of-custody document is required to provide a record of sample transfer from person to person including everyone involved from taking the sample until delivery at the laboratory, and at what time they had the samples. All the personnel need to sign the form with the date and time of day, along with the sample ID code (see also Chapter 8).

3.11 TRANSPORT

When analysis will be performed away from the sampling location, the faecal sludge samples must be packaged and transported. Samples should be delivered to the laboratory as soon as possible following collection, and the travel time and conditions need to be recorded. Samples typically need to be transported in a cooler with ice packs to maintain a sample temperature of 4 °C for the duration of the collection and transport. Faecal sludge sample containers must be packaged in order to protect them and reduce the risk of leakage. Containers should be held upright and cushioned from shock. For more details on samples handling reader is referred to Chapter 8 and reference literature (*e.g.* Rice *et al.*, 2017 and Van Loosdrecht *et al.*, 2016).

3.12 STORAGE AND PRESERVATION

Preservation of samples is crucial to allow reliable analytical results. Sludge composition changes over time, depending on factors such as light, oxygen, temperature and microbial activity, and therefore preservation techniques are required to slow down or stop/inhibit these processes. Analyses should only be done on well-preserved samples, and within the period in which the results will be representative of the initial sludge composition as stated in methods presented in Chapter 8. Samples should always be stored at a temperature of 4 °C to limit biologically induced changes. When several grab samples are collected with the purpose of making a composite, all the grab samples must be stored and preserved at 4 °C during the whole sampling process. Some microbial analysis requires storage preservation at -20 °C or -80 °C for storage longer than 24 hours, whereas samples can be dried and stored for later analysis with acid digestion (*e.g.* heavy metals) or combustion (*e.g.* calorific value, carbon, carbon, hydrogen and nitrogen elemental concentrations). For biologically active samples, it is important to label with an appropriate warning, and to allow gases to vent to avoid explosion.

The same considerations for sample containers need to be considered as discussed in Section 3.5; sampling and storage containers must be made of materials that will not contaminate or react with the

faecal sludge. Polypropylene, polycarbonate, HDPE, Teflon, glass, and stainless steel are relatively inert and are all appropriate for sampling. The cost of Teflon and stainless steel equipment might prohibit or restrict their use, and potential for breakage should be considered with glass. If using steel equipment, depending on the analysis, galvanised or zinc-coated items should not be used because these materials will release zinc into the sample. Other considerations for interaction include silica, sodium, and boron which may be leached from soft glass but not plastic, and trace levels of organics and metals may sorb onto the walls of containers. In all cases, opaque containers are recommended to protect the sample from the light.

The addition of preservatives to the sample container can increase the preservation time of the sample from a few days to a few weeks. However, preservatives also change the composition of the sample and can affect the properties, so their usage has to be carefully evaluated. In this case, it is recommended to only use preservative in a sub-sample of the original sample. Chemical preservatives should only be used when there is no interference with the analyses that are still to be made. However, all methods of preservation may be inadequate when applied to suspended matter. Preservatives should not be added if analysis of volatile, semi-volatile or microbial contaminants are to be done, unless specified methods. For solid sludge samples ('cake' with total solids >25%), adding a chemical preservative is generally not useful since the preservative does not usually penetrate the sludge matrix.

3.13 EXAMPLE OF SAMPLING KIT

An example of a check list for a typical sampling kit is presented in Figure 3.24. For more information on the associated paperwork and health and safety forms, the reader is referred to Chapter 8.

SAMPLING BOX CHECKLIST

Examples of items to take along when sampling

Quantity and sizes will depend on researchers and sampling campaign

Quantity	Contents
1	Mobile First Aid Kit
2	70% Ethanol – 1L
1	1L spray container for any form of disinfection(jik/bleach)
2	Boxes Latex, powder free gloves
2	Pairs plastic elbow length gloves
3	Safety glasses
1	Box PPF2 dust masks
2	Half mask respirators with filters
1	Roll paper towel
1	Pack of bin bags
2	10L square sample containers
5	500ml plastic buckets
1	Small plastic scoop
2	Markers and pens
1	Disinfection soap
1	Sampling form with emergency and contact details
To be added	Overalls, gumboots, cap and water bottle. Increase number of contents depending on the number of researchers sampling.

Figure 3.24 Example from the UKZN PRG of a sampling kit checklist for dry onsite sanitation systems.

3.14 OUTLOOK

The level of accuracy of data is directly linked to the way it is collected, processed, and analysed. To obtain reliable, representative and reproducible values requires a thought-out process, including defining objectives, sampling tools and locations, developing QA/QC procedures, and maintaining a proper chain of custody. Obtaining representative samples from faecal sludge remains a challenge, due to the informal nature, sampling from underground containment, limited access, and inherent high variability of faecal sludge. Hence, it is essential to correctly follow all the steps outlined in methods, and to document any diversions or modifications that occur to ensure that results are replicable. Proper sampling also requires professional training of health and safety risks and adequate personal protection measures.

As faecal sludge management is increasingly established, reliable systematic sampling will play a key role in the development of accurate models for predicting Q&Q of faecal sludge, and management and treatment solutions. Advances in understanding of physical, chemical and biological processes and transformations in the faecal sludge that take place within the onsite sanitation service chain go hand in hand with increased complexity of the descriptors of such processes. In turn, these developments will enable sanitation professionals to tackle practical problems with deeper insight, advanced knowledge and greater confidence.

REFERENCES

- Andriessen N. and Strande L. (in preparation). Manual for assembling and operating Volaser measuring device.
- Andriessen N., Ward B.J. and Strande L. (2019). To char or not to char? Review of technologies to produce solid fuels for resource recovery from faecal sludge. *Journal of Water, Sanitation and Hygiene for Development*, 9(2), 210-224.
- Bassan M., Ferré A., Hoai A.V., Nguyen V.A. and Strande L. (2016). Methods for the characterisation of faecal sludge in Vietnam. Eawag: Swiss Federal Institute of Aquatic Science and Technology. Dübendorf, Switzerland.
- Bassan M., Tchonda T., Yiougo L., Zoellig H., Mahamane I., Mbéguéré M. and Strande L. (2013). Characterisation of faecal sludge during dry and rainy seasons in Ouagadougou, Burkina Faso. Presented at 36th WEDC International Conference, Nakuru, Kenya.
- Beyene A., Tesfahun E., Hailu T., Getaneh A. and Faris K. (2019). Characterisation of Pit Contents and Developing a Scientific Understanding of Processes Occurring in On-Site Dry Pit Latrine Systems in Low-Income Urban Areas in Addis Ababa, Ethiopia. Water Research Commission Project No. K5/2293/11, Pretoria, South Africa.
- Buckley C.A., Foxon K.M., Brouckaert C.J., Rodda N., Nwaneri C., Balboni E., Couderc A. and Magagna D. (2008). Scientific support for the design and operation of ventilated improved pit latrines (VIPs) and the efficacy of pit latrine additives, *Water Research Commission*, Pollution Research Group, School of Chemical Engineering. University of KwaZulu-Natal, ISBN 978-1-77005-718-0.

- Dahmani K. (2010). The development and testing of a portable instrument to determine the filling rates in ventilated pit latrines, University of Kwazulu-Natal and INSA Toulouse (MSc thesis).
- DEP (2005). Sampling Procedures Manual, *Department of Environmental Protection*, State of New Jersey, United States.
- Englund M., Carbajal J.P., Ferré A., Bassan M., Vu T.H.A., Nguyen V.A. and Strande L. (2020). Modelling quantities and qualities (Q&Q) of faecal sludge in Hanoi, Vietnam and Kampala, Uganda for improved management solutions. *Journal of Environmental Management*, 261, 110202.
- GFA Consulting Group BmbH (2018) SFD Report – Lusaka, Zambia.
- Kahn L., Hulls J., Allen B. and Jones J. (2007). The Septic System Owner's Manual, *Shelter Publications Inc.*, United States, ISBN 0936070404.
- Louton B., Beukes L., Naidoo D. and Still D.A. (2018). Understanding and addressing the exposure of workers, the public and the environment to pathogens during pit emptying, Report to the Water Research Commission. ISBN 978143129750.
- Meijer S.C.F. and Brdjanovic D. (2012). A Practical Guide to Activated Sludge Modeling. *IHE Delft*, ISBN 9789073445280.
- Muchiri E.W. (2019). Characterisation of Pit Contents and Developing a Scientific Understanding of Processes Occurring in On-Site Dry Pit Latrine Systems in Low Income Urban Areas in Kenya. Water Research Commission Project No. K5/2302/11, Pretoria, South Africa.
- Prasad P., Andriessen N., Moorthy A., Das A., Coppens K., Pradeep R. and Strande L. (submitted). Methods for estimating quantities and qualities (Q&Q) of faecal sludge: field evaluation in Sircilla, India.
- Radford J. and Sugden S. (2014). Measurement of faecal sludge in-situ shear strength and density. *Water SA*, 40. 183. 10.4314/wsa.v40i1.22.
- Rice E.W., Baird R.B. and Eaton A.D. (eds.) (2017). Standard Methods for the Examination of Water and Wastewater, 23rd edition. American Public Health Association; American Water Works Association; Water Environment Federation. ISBN: 9780875532875.
- Strande L., Schoebitz L., Bischoff F., Ddiba D. Okello, F., Englund, M., Ward, B.J., and Niwagaba C. (2018). Methods to reliably estimate faecal sludge quantities and qualities for the design of treatment technologies and management solutions. *Journal of Environmental Management*. 223(1), 898-907.
- Tembo J.M. (2019). Faecal sludge characterisation for enhanced sanitation provision in peri-urban areas of Lusaka. University of Zambia (doctoral dissertation).
- USEPA (2015). Field Equipment Cleaning and Decontamination Operating Procedure, U.S. Environmental Protection Agency Science and Ecosystem Support Division, Athens, Georgia.
- USEPA (2017). Operating Procedure for Wastewater Sampling. U.S. Environmental Protection Agency Science and Ecosystem Support Division Athens, Georgia, US.
- Van Loosdrecht M.C.M., Nielsen P.H, Lopez-Vazquez C.M., Brdjanovic D. Ed. (2016). Experimental Methods in Wastewater Treatment. *IWA Publishing*, ISBN 9781780404745 (Hardback) 9781780404752 (eBook).
- Velkushanova K.V., Zuma L. and Buckley C. (2019). Mechanical properties of faecal sludge. *Gates Open Research*, 3, 1582.
- Ward B.J., Gueye A., Diop B., Traber J., Morgenroth M. and Strande L. (2019). Evaluation of conceptual model and predictors of faecal sludge dewatering performance in Senegal and Tanzania. *Water Research*, 167, article 115101.
- Ward, B.J., Andriessen, N., Tembo, J.M., Kabika, J., Grau, M., Scheidegger, A., Morgenroth, E., Strande, L. (2021) Predictive models using cheap and easy field measurements: Can they fill a gap in faecal sludge monitoring and process control? *Water Research*. <https://doi.org/10.25678/00037X>.
- World Bank, ILO, WaterAid, and WHO (2019). Health, Safety and Dignity of Sanitation Workers: An Initial Assessment. World Bank, Washington, DC.
- Zuma L., Velkushanova K. and Buckley C. (2015). Chemical and thermal properties of VIP latrine sludge. *Water SA*, 41(4), 534-540.
- Zziwa A. (2019). Characterisation of Pit Latrine Contents and Developing a Scientific Understanding of Processes Occurring in On-Site Dry Pit Latrine Systems in Low Income Urban Areas: A Case Study of Kampala Suburbs. Water Research Commission Project No. K5/2301/11, Pretoria, South Africa.

4

Experimental design for the development, transfer, scaling-up, and optimisation of treatment technologies: case studies of dewatering and drying

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OBJECTIVES

The objectives of this chapter are to:

- Introduce scales of experimentation and experimental design for the development, transfer, scaling-up, and optimisation of faecal sludge treatment technologies
- Provide examples of experimental approaches for scaling-up conditioners for dewatering and drying for resource recovery
- Present case studies that address research questions at different scales of faecal sludge treatment processes and technology development and adaptation.

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4.1 INTRODUCTION

This chapter provides a methodology for experimentation in developing treatment technologies for faecal sludge management. A methodology helps to ensure that results are reproducible, reliable for application to design, and available for further interpretation. Experimentation is used to learn about how physical, chemical and biological principles can be employed to achieve defined objectives. In the field of sanitary engineering, an overarching goal is the protection of public and environmental health. With this in mind, sanitary engineers have been active in experimental work around centralised wastewater treatment for more than a century (Stensel and Makinia, 2014; Van Loosdrecht *et al.*, 2016). Developments have included physical, biological, and chemical advances in wastewater treatment plants, first pertaining to removal of solids and organics, then nutrients, and now even micropollutants and trace contaminants. Experimental work has helped to understand fundamentals, develop technologies, and scale up and optimise process trains and treatment steps. More recently, there has been a focus on faecal sludge management (FSM), also known as non-sewered sanitation (NSS). The importance of FSM has been gaining acknowledgement, and is recognised as a long-term sustainable solution. A major challenge now is to use experimental work to fill the comparative gap in knowledge, and to develop full-scale, operational solutions for FSM. This will require experimentation to determine how faecal sludge (FS) behaves with different treatment technologies, in order to scale up and design reliable full-scale treatment facilities.

The current state of knowledge in faecal sludge treatment covers technologies that are either *established*, *transferring*, or *innovative* (Strande, 2017; WHO, 2018). *Established technologies* are those where adequate knowledge exists on how to make recommendations for their full-scale design and operation to protect public and environmental health. Examples of established technologies include settling-thickening tanks, drying beds, co-composting, and stabilisation ponds. Experimentation is important for established technologies in order to optimise their use and performance, to further understand treatment

performance and mechanisms, and to monitor in order to ensure treatment performance is adequate. *Transferring technologies* are those that are already established in other applications, such as wastewater treatment, and appear promising for use in FSM. Their use has not yet been widely established in FSM, but ongoing research is helping to establish their use and effectiveness. Examples of transferring technologies include mechanical dewatering, conditioners, alkaline treatment, incineration, anaerobic digestion, pelletising, geotextiles, and thermal drying. Research and experimentation are very important in the transfer of these technologies, because faecal sludge is highly variable and very different in composition from the mixed domestic wastewater for which most biological wastewater treatment plants are designed. *Innovative technologies* are new and emerging technologies that are still under development and not yet established. Due to the level of unknowns, the level of expertise required to design and operate these technologies in a fashion that adequately manages risks is much greater than with established technologies. As further research is carried out, many of them will also become established technologies. Examples of innovative technologies include, but are not limited to, the use of black soldier fly larvae, and ammonia treatment (Chapter 2).

The four main treatment objectives that need to be addressed for sustainable faecal sludge management are (i) stabilisation, (ii) nutrient management, (iii) pathogen inactivation and (iv) dewatering/drying (Niwigaba *et al.*, 2014). In this chapter, experimentation for the purpose of scaling-up dewatering and drying experience are provided as examples of implementation of the presented methodology. Dewatering is defined here as removal of free water and water that is loosely bound in pores and interstitial spaces of sludge particles and flocs (Figure 4.1). Depending on the properties of faecal sludge, it can be dewatered to between 70 and 80% moisture by weight, or 20 to 30% dry solids. Drying is defined here as the further removal of water from the solids fraction following dewatering, for example water trapped within cells or bound to particle surfaces.

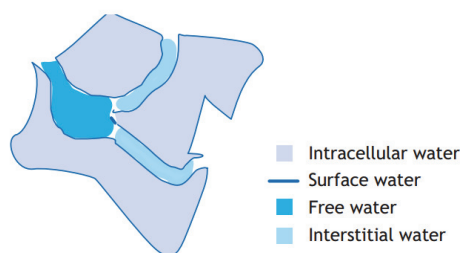


Figure 4.1 Representation of the different forms of water in a sludge floc (adapted from Bassan et al., 2014)

This chapter first discusses the general scales of experimental work and introduces a methodology for experimental design and how to apply these concepts to faecal sludge treatment processes. This is followed by background information that is necessary to apply the concepts for scaling-up dewatering and drying, together with five case studies: two for conditioning for improved dewatering, and three for thermal drying for energy recovery. The background and case studies provide examples of how to implement the methods presented in Chapter 8. Prior to conducting experiments at any scale, preliminary research must first be completed. This includes a literature review to learn from experience, and to ensure efforts are not unnecessarily replicated.

In this era of virtual communication, open access to many materials and online communities of researchers and practitioners has made it easier to share findings and obtain feedback and support. To put this advantage to good use, the sharing of research results and raw data is strongly encouraged.

4.2 EXPERIMENTATION IN FAECAL SLUDGE MANAGEMENT

Before starting experiments, it is important to become familiar with the key elements used in setting up experimental work. Experiments are a way to understand cause-and-effect relationships in a system, by deliberately changing conditions in a controlled fashion, and observing the changes in the system that are produced as a result of what has been altered. An experiment can be defined as ‘a series of runs in which purposeful changes are made to the input variables of

a process or system so that we may observe and identify the reasons for changes that may be observed in the output response’ (Montgomery, 2019). A run is one component of an experiment, conducted with a specific set of input variables. Tests are measurements of specific faecal sludge characteristics or properties, as described in chapters 2 and 8. Tests can be part of an experiment (e.g. measuring pathogen levels in treated faecal sludge), but can also be conducted outside of a planned experiment. For example, laboratory tests are used for routine characterisation to monitor the performance of existing treatment systems.

4.2.1 Scales of experiments

In the development and scaling-up of treatment technologies, reasons for experimentation will include developing fundamental knowledge (e.g. mechanisms controlling dewaterability), designing and developing new processes or technologies (e.g. LaDePa), and transferring and optimizing existing technologies (e.g. geotextiles, pelletisers, and conditioners). To accomplish this, the different levels of laboratory-, pilot-, and full-scale experimentation are employed depending on the stage of development and specifically defined objectives.

Laboratory-scale experiments

Laboratory-scale experiments are conducted in a laboratory, often using existing conventional analytical equipment and Standard Operating Procedures (SOPs). This is the smallest, bench-scale for experimentation, typically using low volumes of faecal sludge (i.e. mL to several L). Laboratory-scale experiments allow for controlled conditions when the experimenter wants to investigate the isolated effects of specific process parameters. This scale of experimentation lends itself well to comparisons with results from other researchers, as they should be replicable in other laboratories with the same setup. One caveat is variability in faecal sludge, which can be addressed through experiments that include simulant faecal sludge, as presented in Chapter 7. Laboratory-scale experimentation is also often used for establishing proof-of-concept for a new technology, and answering questions about fundamentals and mechanisms involved with faecal sludge treatment.

Pilot-scale experiments

Pilot-scale experiments are regarded as a necessary step on the way from laboratory-scale research to full-scale process optimisation and implementation (Wood-Black, 2014). Typical pilot-scale experiments operate at capacities between 50-2,000 L of faecal sludge per day. Pilot-scale experiments help to answer questions about practical operation and feasibility of the process. Reasons for piloting a treatment process can be predicting costs and energy requirements, establishing the needs for process control, understanding practical operating conditions, and anticipating any potential unforeseen impacts of adopting a new technology or process unit on the rest of a faecal sludge treatment plant (FSTP). Pilot-scale experiments can ultimately be used to determine whether it is feasible to implement a new technology at full-scale.

Full-scale experiments

Full-scale experiments are conducted at existing FSTPs that have been designed for treatment capacities ranging from 1,000 - 800,000 L of faecal sludge per day (Klinger *et al.*, 2019). Experiments that take place at full-scale are used to optimise FSTP performance. The FSM sector is undergoing rapid change, so transitions from pilot- to full-scale application for many treatment processes is expected to happen with increasing frequency in the near future. However, while full-scale experiments are necessary to make faecal sludge treatment as effective, efficient, robust, and sustainable as possible, they must always be balanced with the responsibility of maintaining certain standards of treatment for the protection of public and environmental health.

Working with faecal sludge and with transferring or innovative treatment technologies inherently includes uncertainties and risks that need to be managed. The transitions between laboratory-, pilot-, and full-scale experiments may be iterative and will require time and dedication to achieve high-quality experimental design and execution. It is critically important to incorporate a research component into any faecal sludge treatment project from its inception. Risks can be mitigated by forming partnerships between municipalities and universities/research institutes, which can help guide experimentation from

the start of the project to the optimisation and monitoring of a full-scale FSTP (Strande, 2017).

4.2.2 Designing an experiment

After identifying the purpose, rationale, and scale of experimentation, the following guidelines adapted from the book *Design and Analysis of Experiments* (Montgomery, 2019) can be used to design experiments. Montgomery (2019) can also be consulted for detailed information about experimental design and statistical analysis for process engineering. In addition, information on experimental methods is available in Van Loosdrecht *et al.*, 2016 and on experimental data handling and analysis in Von Sperling *et al.*, 2020.

The experimental design guidelines are presented here, together with examples specific to helminth inactivation during drying (in italics):

1. Specify the research question.
What is the optimum retention time for drying of faecal sludge in an infrared dryer to achieve complete helminth inactivation?
2. Select the response variable to measure.
Mean percentage viability of helminths after drying.
3. Identify relevant design factors, levels, and ranges over which the experiment should operate.
Infrared drying technology can operate over the range of 105-125 °C, so the retention time will be evaluated at 105, 115, and 125 °C. Retention times of 10, 30, 60, and 120 seconds will be evaluated at each temperature.
4. Identify factors that could influence the response variable, and evaluate if they can be kept constant during the experiment.
Moisture content of air, characteristics of faecal sludge.
5. Identify laboratory methods and SOPs to measure the response variable, influencing factors, and operating conditions.
See Section 8.9.3 Helminth Method.
6. Determine how many replicates to run to determine the uncertainty in your response variable.
Triplicate runs for each combination of temperature and residence time.

7. Develop a QA/QC protocol to ensure meaningful results (e.g. standards, blanks, duplicates).
Use Ascaris suum egg standards with known egg count and percentage viability as a positive control, and sludge simulant as a negative control. Prepare 3 positive controls by spiking sludge simulant with Ascaris suum egg standards. Once the drying experiments have been carried out, test the negative control and positive controls along with the test samples, as per Section 8.9.3 Helminth Method.
8. Perform the experiment.
Carry out experiments as previously described; write down any deviations from the original plan.
9. Interpret the results.
Visual inspection of data, graphs, statistical interactions, and empirical models.
10. Define the next steps based on conclusions and recommendations from interpretation of the results.
All residence times tested at 125 °C yield complete helminth egg inactivation; 10 seconds is the recommended residence time based on these results. Conduct further tests on a broader range of sludges, and a cost-benefit analysis of the operating temperatures.

Presented in this chapter are five case studies for dewatering and drying of faecal sludge, together with adequate background information for understanding of the case studies.

4.3 TRANSFERRING TECHNOLOGY: CONDITIONING TO IMPROVE DEWATERING

Presented in this section is background information on the use of conditioners to improve dewatering of sludge, followed by two real-life case studies of experimental design for faecal sludge conditioning processes.

4.3.1 Introduction to faecal sludge dewatering with conditioners

Prior to dewatering, faecal sludge can be up to 99% water by weight. Separation of solids and liquids is required in order to fully treat the liquid fraction before end use or discharge into the environment. It is

also required before treatment of the solids fraction for disposal or end use, and enables more efficient transportation of the solids fractions.

Separating the solids and liquids in faecal sludge can be achieved through settling (e.g. settling-thickening tanks), filtration (e.g. drying beds or geotextiles), or mechanical methods (e.g. screw presses, filter presses, or centrifuges). Settling-thickening tanks (Figure 4.2) and drying beds (Figure 4.3) are widely-used, established technologies for faecal sludge treatment, however they require large areas of land and long residence times to sufficiently dewater sludge.



Figure 4.2 Settling-thickening tanks at Lubigi FSTP in Kampala, Uganda (photo: Eawag).



Figure 4.3 Drying beds at Niayes FSTP, Dakar, Senegal (photo: Eawag).

Depending on its specific properties, sometimes sludge dewaterers more quickly and thoroughly, and other times dewatering performance is quite poor. To address this, transferring technologies from wastewater treatment, such as geotextiles (Figure 4.10, Case study 4.2) or mechanical presses are being considered to increase throughput and treatment performance, and reduce footprint. However, these transferring technologies do not reliably or predictably perform without the addition of dewatering aids called ‘conditioners’.

Conditioners are chemicals that are used to improve dewatering and settling performance. They are well-established in wastewater and water treatment, food processing, and the pulp and paper industry, which have relatively more homogenous waste streams than faecal sludge. Empirical and observational knowledge is starting to be gathered about conditioning of faecal sludge at the laboratory- and pilot-scale, but very little fundamental knowledge is available. Further experimentation at all scales will be necessary to scale up the use of conditioners.

Conditioners are mixed into a slurry or suspension, and added to sludge during treatment at optimal ‘doses’. Selection of the optimal conditioner and dose of that conditioner are based on physical and chemical characteristics of the sludge to be dewatered. Accurate dosing is required, as both under-dosing and over-dosing result in poor flocculation, which results in quickly clogged filters and slow or incomplete dewatering performance (*i.e.* increased organic loadings in the filtrate, clogged or blocked drying beds or geotextiles, and higher residual moisture in dewatered faecal sludge). Dosing needs to be frequently reassessed and varied in response to changes in influent characteristics, and is based on online monitoring, making the high variability in quantities and qualities of influent faecal sludge currently a barrier to implementing them at scale.

Recent research on the optimal dosing of conditioners for faecal sludge has been based on laboratory testing, which is too time- and labour-intensive to be scaled up. However, it indicates that when the right conditioner and dose are applied, significant improvements to faecal sludge dewatering

performance are possible; for example, faster dewatering on drying beds, and cleaner effluent from drying beds, settling-thickening tanks, and geotextiles (Gold *et al.*, 2016). Research needs to be directed at developing methods to rapidly characterise influent faecal sludge quantities and qualities (Q&Q, see Chapter 5) to determine the conditioner dose (Gold *et al.*, 2018, Ward *et al.*, 2019). In addition, considerations such as cost, availability, supply chain, chemical safety, and possible requirement of additional infrastructure (storage tank, dosing device, mixing tank) need to be taken into account when designing experiments and selecting conditioners and dosing processes to apply at pilot- and full-scale.

4.3.2 Types and mechanisms of conditioners

The following section has been adapted from Chapter 5 (Section 5.2) of the book *Faecal Sludge Management: Highlights and Exercises* (Ward and Strande, 2019), and provides additional background information on the use of conditioners to improve dewatering performance of faecal sludge, and methods for measuring performance.

Conditioners can be inorganic chemicals such as lime, ferric chloride or aluminium sulphate, or they can be charged polymers (‘polyelectrolytes’). Polymers can be locally produced from natural materials, such as chitosan or *Moringa oleifera*, or can be proprietary materials sourced from chemical companies. It is expected that cationic (positively charged) polyelectrolytes will work best with faecal sludge, as they will be more likely to interact with organic particles, which are negatively charged. Conditioners work by destabilising small suspended particles to form larger aggregates (shown in Figure 4.4). This happens through coagulation, which is the initial destabilisation and aggregation of colloidal particles. This is followed by flocculation, which is the formation of larger particles, or ‘flocs’, from smaller particles.

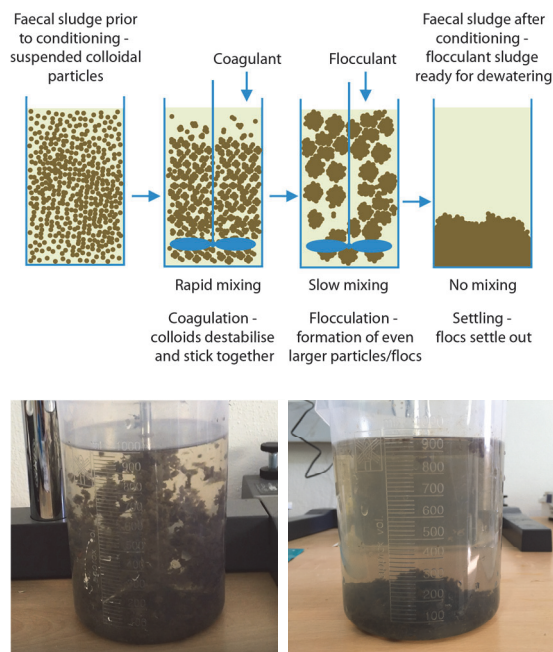


Figure 4.4 Above: steps in faecal sludge conditioning, coagulation, flocculation, and sedimentation; below left: flocculation of faecal sludge; below right: settling of faecal sludge flocs (figure: adapted from Ward and Strande, 2019, photos: IHE Delft).

4.3.3 Key parameters for selection of conditioners and optimal dose

The selection of conditioners and the optimal dosage is specific to the faecal sludge properties, the dewatering technology, and the mixing conditions of the chemicals with the sludge.

- **Faecal sludge properties:** conditioners are commonly dosed as a function of total suspended solids, or with faecal sludge often total solids is used in the absence of total suspended solids measurements. Other factors such as the electrical conductivity or the degree of stabilisation may influence which type of conditioners work best.
- **Dewatering technology:** conditioners need to be compatible with technologies used for dewatering. For example, centrifuge dewatering requires conditioning with polymers that produce flocs that are resistant to high shear (*i.e.* very high molecular weight, and usually branched or structured polymers).

- **Mixing conditions:** complete mixing of faecal sludge with conditioners is necessary to make the particles collide and stick together (coagulate) and grow into flocs (flocculate); however, mixing speeds need to be selected to avoid floc destruction. Mixing for coagulation needs to be vigorous in order to cause many particle collisions. However, mixing for flocculation needs to be gentle to keep flocs from breaking up. This should also be considered during the selection of pumps for example, for the transfer of conditioned faecal sludge from a settling-thickening tank to a drying bed.

Use of conditioners will also impact the properties of the dewatered faecal sludge, which needs to be taken into account when designing further process steps. Conditioners can increase total solids production, and affect the rheology and water-binding behaviour of the conditioned sludge.

4.3.4 Laboratory- and pilot-scale testing

The following methods used to evaluate the suitability of conditioners in faecal sludge are included in the Chapter 8:

- **Jar test:** a common method for testing conditioner performance at different doses. Faecal sludge is mixed with different doses or different types of conditioner. After mixing, the settling and/or dewatering performance of the conditioned faecal sludge is compared to unconditioned faecal sludge (Figure 4.5).
- **Sludge volume index (SVI):** a metric for settling performance using Imhoff cones (Figure 4.6).
- **Chemical oxygen demand (COD):** a metric for organic loading in the supernatant after settling, or in the filtrate after filtering.
- **Total suspended solids (TSS):** a metric for particulate loading in the supernatant after settling, or in the filtrate after filtering.
- **Capillary suction time (CST):** a metric for dewatering time (Figure 4.7).
- **Dewatered cake dryness:** a metric for dewaterability, determined by dewatering using a centrifuge or a lab-scale filter press. Dry solids fractions in the dewatered sludge cake are measured and compared.



Figure 4.5 Example of a jar test setup to test suitability of a conditioner (photo: Eawag).



Figure 4.6 Example of an SVI settling test setup with graduated Imhoff cones (photo: Eawag).



Figure 4.7 Example of replicates being measured in a CST test to determine sludge dewatering time (photo: Eawag).

At the pilot-scale, similar experiments can be conducted with settling-thickening columns, pilot-scale drying beds, or pilot-scale mechanical presses. Specific considerations when transitioning from laboratory experiments to pilot-scale conditioner trials include mixing conditions and sampling protocols. Replicating mixing speed and turbulence achieved during laboratory-scale jar tests is often difficult at pilot-scale. The shape and power of the mixer, and shape and aspect ratio of the mixing tank influence the completeness of mixing, and may therefore alter the optimal dose. Sampling protocols are another point to consider when scaling-up. If the pilot-scale experiments require a comparison of faecal sludge properties before and after conditioning, mixing, and dewatering, the pilot facility should be designed to accommodate this.

4.3-5 Case studies – conditioning for improved dewatering

In the following case studies, examples are provided of (i) a laboratory-scale comparison of different conditioners followed by discussion of how to implement pilot-scale testing on drying beds, and (ii) an account of a pilot-scale study of online conditioner dosing combined with geotextile dewatering, with lessons learned for full-scale implementation.

Case study 4.1 *Evaluating conditioners produced from locally-available materials for improved faecal sludge dewatering in Dar es Salaam, Tanzania*

This case study is based on a two-year Master's project by Nuhu Moto at the University of Dar es Salaam (UDSM), a collaborative project between Eawag and UDSM in Dar es Salaam, Tanzania (Moto *et al.*, 2018). This project was motivated by the desire to increase the capacity of unplanted drying beds at an FSTP. Laboratory-scale experiments were conducted to find out whether conditioners could be a possible treatment option for faecal sludge in Dar es Salaam. Two conditioners, which could be produced from locally-available materials, were compared using jar tests, and conclusions were drawn about which conditioners and which doses to select for pilot-scale drying bed trials.

Research question

Which locally-available conditioners and at which doses should be selected for pilot-scale trials?

Response variables

- CST was used to quantify filtration time.
- TSS of the supernatant after settling was used to quantify particulate removal.

Factors, levels, and ranges

- Type of conditioner tested.
Two types of conditioners that could be manufactured from locally-available natural materials were tested: chitosan and *Moringa oleifera*.
- Conditioner dose
0, 1, 2, 3, 5, and 8 mg/gTS for chitosan and 0, 10, 50, 100, 250, 500, 750, 1,000 mg/gTS for *M. oleifera*

Factors that might influence the response variables

- Mixing speeds and durations and beaker size/shape can influence results of a jar test. To avoid interference from these factors, consistent mixing speeds, mixing durations, and beakers were used for all of the jar tests.
- Physical-chemical characteristics of faecal sludge (TS, TSS, pH, conductivity) can affect how well a conditioner works. To account for this, one large faecal sludge sample was used for every jar test, and care was taken to homogenise the sample well so that all the beakers contained representative sludge. To make sure that they were not selecting the best conditioner and dose for just one specific batch of sludge, jar tests were run with multiple faecal sludge samples.
- Faecal sludge processing procedures (e.g. homogenising with a blender) can change the dewatering performance of a sludge. Blending can disrupt particles and flocs, which can change dewatering behaviour, so homogenisation was done by hand mixing so as to not destroy particles.

Experimental design details

The number of replicates was based on suggestions in standard methods for specific SOPs. An optimal conditioner dose was defined as the lowest dose that achieves > 75% reduction of CST (based on literature, explained in Ward and Strande, 2019).

Interpreting the results

To determine the optimal doses of chitosan and *M. oleifera*, jar tests were performed with the following concentrations of conditioners, and the CST and TSS of supernatant were measured. Results for CST are shown in Table 4.1 and Figure 4.8. Trends in TSS were similar to trends in CST, and are not shown.

Table 4.1 Results of jar tests to determine the effect of different doses of conditioners chitosan and *M. oleifera* on CST reduction.

Conditioner	Dose (mg/gTS)	Reduction in CST (%)
Chitosan	0	0
	0.5	45
	1	60
	2	79
	3	88
	5	90
	8	92
<i>M. oleifera</i>	0	0
	10	13
	50	25
	100	33
	250	68
	500	83
	750	87
	1,000	80

The results indicated that for this sludge, the optimal dose of Chitosan is approximately 2-3 mg/gTS, and the optimal dose of *M. oleifera* is approximately 250-500 mg/gTS (the red dots in Figure 4.8).

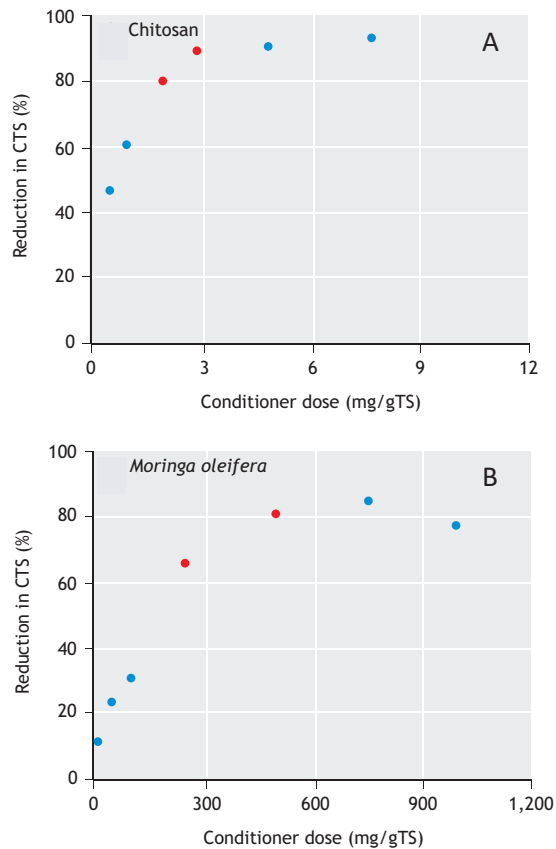


Figure 4.8 A) Results of jar tests with chitosan. B) Results of jar tests with *M. oleifera*. The red dots indicate the optimal dose of each conditioner.

Scaling-up from laboratory to pilot-scale

Both conditioners that were tested achieved similar performance in terms of CST and TSS reduction, but the optimal doses for each were very different. In Dar es Salaam, chitosan was estimated to cost 15 US\$/kg and *M. oleifera* 30 US\$/kg. The cost of each conditioner at optimal dose for 1 tonne of faecal sludge (with TS of 10 g/L) would be 0.38 US\$ for chitosan and 112 US\$ for *M. oleifera* (see Ward and Strande, 2019 for full details). Because *M. oleifera* was prohibitively expensive at the optimal dose, only chitosan was chosen to proceed to the pilot-scale trials (Figure 4.9).



Figure 4.9 A) mixing chitosan conditioner for pilot-scale trials. B) the pilot-scale dewatering research facility at the University of Dar es Salaam, including the settling-thickening tanks, conditioner mixing tank, and six sand drying beds (photos: Eawag).

New research questions were developed for the pilot-scale experimentation, including:

- Does chitosan decrease residence time on unplanted drying beds?
- Can chitosan be used to condition every batch of incoming faecal sludge, or does it only work for sludge with certain physical and chemical characteristics?

- Does the benefit of reduced residence time on drying beds justify the cost of conditioners?

For more information on the results, refer to Moto *et al.*, 2018.

Case study 4.2 *Scaling-up conditioner dosing for full-scale faecal sludge dewatering*

This case study is based on research by Naomi Korir, Jonathan Wilcox, and Catherine Berner at Sanivation in Naivasha, Kenya. This pilot-scale research was done to inform the design of a full-scale dewatering process for a new FSTP in Naivasha, Kenya (capacity 4,000 tonnes faecal sludge per month, delivered by vacuum trucks from pit latrines and septic tanks). Requirements for the plant included a small treatment footprint for the dewatering step, and economic viability. Previous laboratory-scale research characterised hundreds of samples of faecal sludge from Naivasha and established the selection of polymer conditioner and the optimal dose for flocculation. Sanivation wanted to scale up dewatering with geotextiles. To do this requires experimentation for the online dosing, as presented in Section 4.3.1. Because of the iterative experimental approach, questions should be answered one at a time. Therefore the following experiments were carried out on the assumption that geotextiles would work. The pilot-scale setup was sized to process sludge from one vacuum truck at a time, and was designed to test

different online conditioner dosing and mixing configurations followed by a subsequent dewatering step using geotextile skips suspended on metal supports (Figure 4.10).

Research question

What is the optimal configuration for online dosing and mixing of conditioners?

Response variables

Sanivation defined the ‘optimal’ dosing configuration as one that yields fast dewatering and low solids loading in the filtrate while requiring the lowest possible conditioner cost.

- Dewatering time was the amount of time it took for sludge to dewater in geotextile skips (residence time); sludge was considered ‘dewatered’ when it reached 15-20% TS (80-85% moisture). This benchmark was chosen as it is the required input dryness for Sanivation’s heat treatment method, the next step in the treatment process.
- Filtration efficiency was used to quantify how well the geotextiles filtered solids from the incoming faecal sludge. Filtration efficiency was calculated using measured values of TSS of the influent faecal sludge (TSS_{FS}) and of the filtrate leaving geotextile skips ($TSS_{filtrate}$), using the following equation:



Figure 4.10 A) a geotextile skip setup at the pilot facility; B) a geotextile skip being loaded with conditioned faecal sludge; C) dewatered sludge ready to be unloaded from a geotextile skip (photos: Sanivation).

$$\text{Filtration efficiency} = \frac{\text{TSS}_{\text{FS}} - \text{TSS}_{\text{filtrate}}}{\text{TSS}_{\text{FS}}} \quad (4.1)$$

Every batch of filtrate was also characterised for TS, COD, BOD, ammonia and nitrates, to understand the removal of different pollutants by the geotextiles, and the type of treatment that would be required to treat the liquid effluent to required standards (NEMA Standards).

- Cost of polymer per tonne faecal sludge was used to predict material costs for a full-scale process.

Factors, levels, and ranges

- Dosing configurations: different numbers of dosing ports (one or multiple dosing ports) and different mixing conditions (no mixing, mixing with baffles, mixing with a mechanical stirrer) were tested (Figure 4.11). Figure 4.12 shows the actual setup.

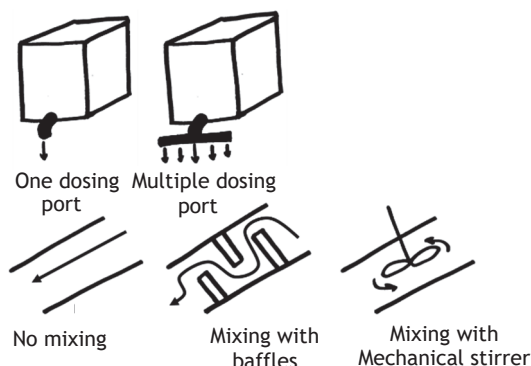


Figure 4.11 Diagram representation of the different conditioner dosing and mixing configurations evaluated by Sanivation.

- Conditioner doses: the laboratory-scale conditioner experiments indicated that the optimal polymer conditioner dose was 2 g polymer per kg faecal sludge; however, the Sanivation team suspected that due to different mixing conditions at the pilot-scale, the optimal dose for the scaled up process could be different. Doses of 2-60 g polymer per kg faecal sludge were tested at the pilot-scale.
- Geotextile cleaning methods: geotextiles were cleaned to determine whether their lifetime could

be extending by cleaning between receiving batches of faecal sludge. Three cleaning methods were investigated detergent, detergent + salt, detergent + salt + high-pressure water rinse (Figure 4.12).



Figure 4.12 A) a Sanivation employee washes detergent, salt, and particulate residue from a geotextile using a high-pressure water rinse and B) example of a conditioner dosing configuration: one dosing port followed by mixing with baffles (photos: Sanivation).

Factors that might influence the response variables

- Age of the geotextile/frequency of cleaning can affect dewatering time. New geotextiles dewater quickly (several minutes for septic tank faecal sludge, several hours for pit latrine faecal sludge), but older geotextiles require more time. To account for this, trials were carried out with three geotextile skips that were the same age and had undergone the same cleaning regimen.
- Weather: rain and humidity can affect how long it takes sludge to dewater, since geotextile boxes were open to the air and could gather rainwater. To account for this, the Sanitation team set up a tray that was exposed to the same conditions as the geotextiles. At the end of the study, no rainwater had accumulated in the tray. Physico-chemical characteristics of sludge can change the optimal dose and dewatering speed. Every batch of incoming faecal sludge was characterised for TS, TSS, COD, BOD, ammonia and nitrates. Sanitation engineers designed different conditioner dosing flow rates for pit latrine sludge and septic tank sludge to account for higher levels of observed TS in sludge from pit latrines and lower levels observed in septic tanks.

Experimental design details

Each dosing configuration and each geotextile cleaning method were typically trialled with at least one batch of pit latrine sludge, and one batch of septic tank sludge. If the first repetition was not successful, then further replicates were not completed. For promising configurations, more replicate testing was performed to determine the reproducibility and variability of performance.

Interpreting the results

The optimal conditioner dose was not directly transferable from lab-scale studies to pilot-scale. Different, less ideal mixing conditions at the pilot-scale called for increased doses of polymer to be used to account for incomplete mixing with sludge particles. Multiple dosing ports performed better than a single port, and the addition of both baffles and mechanical mixing led to the most thorough mixing of conditioner and subsequently the shortest dewatering times in the geotextile skips (less than 5 days compared to 14 days with not optimal conditioner

dose) and highest filtration efficiency. With the optimal setup, polymer doses from 2-8 g/kg produced the best results. Overdosing occurred at doses over 8 g/kg, resulting in immediate clogging of the geotextiles and a prolonged dewatering time. The team continued to experience issues with achieving precise dosing with respect to TS. Because of this, it was difficult to avoid overdosing even when doses < 8 g/kg were targeted.

Geotextiles were able to be reused after employing the optimal cleaning method: detergent + salt + high-pressure washing. After cleaning, geotextiles were restored to about 30% of the performance of original unused geotextile at negligible material cost increase. However, cleaning was labour-intensive and required 1.5 hours of work to clean every bag after every loading/unloading cycle.

Scaling-up from pilot to larger-scale FSTP

Based on their performance at pilot-scale, the Sanitation team decided not to scale up geotextile skips. This decision was based on the estimated land area required for dewatering using performance data from optimised dosing, mixing, and geotextile cleaning processes in place (with mechanical mixing, multiple dose ports, and cleaning between every load cycle). The average residence time in the geotextile skips at optimal conditions was 5 days per truckload. The full-scale FSTP is designed for a capacity of 20-25 truckloads per day, and the footprint of a geotextile skip is 8 m². In the best-case scenario involving constant operation 7 days/week and just one day to unload and clean a geotextile skip, 150 geotextile skips would be required, which means 8 m² · 150 = 1,200 m² or 0.12 hectares of land would be required for dewatering (10% of the entire land allotment for the new FSTP). Labour costs were also a significant factor in the decision not to scale up geotextiles. Sanitation also identified that geotextiles can be reused for dewatering up to 10 times with washing in between loadings.

Sanitation is moving forward with the design and implementation of their full-scale FSTP, and will proceed with their optimal polymer dosing configuration. However, the team will switch to a screw press as an alternative, lower-footprint

technology. The screw press technology is more resilient to overdosing and the team hopes it will not clog as easily as geotextiles. Screw presses operate continuously instead of being batch processes, allowing for a higher throughput of 20 m³ sludge per hour. The allotted footprint of the full-scale dewatering process is 120 m², an order of magnitude lower than geotextiles would have allowed. Piloting experiments with screw presses are now planned in order to inform the FSTP design. New research questions can be asked, for example, ‘What are the optimal operation conditions of the screw press (hydraulic loading rate, conditioner dose, wash water flow rate)?’.

Fast, easy, and reliable methods for online measurements to adjust conditioner doses are still lacking. This is one of the key research topics that needs to be addressed in order to avoid overdosing and reduce conditioner costs. Research is actively being pursued to advance this knowledge (Ward *et al.*, 2021). When accurate methods for online dosing have been adequately developed, the use of geotextiles will be more readily transferable to faecal sludge. However, there are other cases where geotextiles are currently being successfully employed for dewatering, for example, the Dumaguete FSTP in the Philippines (Strande, 2017).

4.4 TRANSFERRING TECHNOLOGY: THERMAL DRYING FOR RESOURCE RECOVERY OF DRIED SLUDGE FOR ENERGY

Presented in this section is background information on thermal drying of sludge, followed by three real-life case studies of experimental design for thermal drying processes.

4.4.1 Introduction to resource recovery of faecal sludge as solid fuel

Producing value-added end products from faecal sludge can be an incentive for appropriate management and treatment. Revenue from resource recovery can be used to offset operational and maintenance costs at FSTPs, which can incentivise adequate collection and delivery of sludge to treatment plants and achievement of consistent

treatment targets (Diener *et al.*, 2014). A market-driven approach should be used to determine the revenue potential from possible end products of faecal sludge treatment (Schoebitz *et al.*, 2016). In Accra, Ghana and in Kampala, Uganda, use as a solid fuel for manufacturing industries (*e.g.* brick and cement factories) was identified as a high-demand end product of faecal sludge (Diener *et al.*, 2014). Many industries in these cities typically rely on wood and waste biomass, and struggle when availability of these fuels fluctuates. Solid fuels produced from faecal sludge can have comparable energy densities to these traditionally used fuels (Andriessen *et al.*, 2019; Gold *et al.*, 2017; Murray Muspratt *et al.*, 2014). The decision to target resource recovery allows FSTP designers to set treatment targets based on the requirements set by the consumers (*e.g.* moisture content, energy density, pathogens), and select appropriate treatment technologies accordingly.

4.4.2 Introduction to faecal sludge drying

Drying is a requirement for producing solid fuels from faecal sludge. In addition to increasing net energy gains (Murray Muspratt *et al.*, 2014; Septien *et al.*, 2020), drying also reduces the mass, making it easier to handle and decreasing transportation costs. Drying can be achieved passively, for example with drying beds, but this requires a large footprint and long residence times (weeks to months). Hence, researchers are pursuing heat drying of dewatered faecal sludge as a transferring technology from the food processing industry. One example is the LaDePa process, developed by the eThewkini municipality and Particle Separation Systems (Durban, South Africa). The LaDePa can be used at a full-scale treatment plant to dry and pasteurise sludge from ventilated improved pit latrines (VIPs) (see Case study 4.4 and Septien *et al.*, 2018a). Another example is the Tehno Sanitizer® (also known as The Shit Killer®), based on microwave technology that has been used for food drying for years (*e.g.* pasta, fruit etc., see Case study 4.5). Requirements for how much moisture needs to be removed are dictated by the treatment process design and by the end-user requirements. Different technologies require different input moisture contents, and further drying may be necessary after sludge has been processed (Figure 4.13).

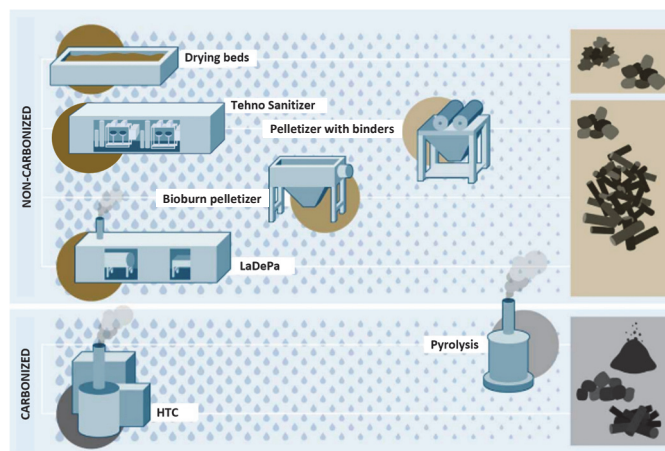


Figure 4.13 An overview of technology options for producing solid fuel, starting from dewatered faecal sludge at 80% moisture and ending at non-carbonised or carbonised solid-fuel end products. The position of the technology icons from left to right indicates the required dryness of the input sludge for each technology, as indicated by the size of the droplets, ranging from 80% moisture on the left to 10% moisture on the right (modified from Andriessen et al., 2019).

In general, solid fuels do not perform well if they contain too much moisture, but this needs to be balanced with higher energy inputs or longer drying times.

It has been difficult to adapt and scale up drying technologies to full-scale faecal sludge treatment processes. Drying technologies face many of the same challenges as any faecal sludge treatment process, for example high variability in Q&Q of the influent sludge. However, drying faecal sludge presents its own specific technical challenges as well. These include the high energy demand, the release of strong odours during drying, and the stickiness acquired by faecal sludge during the drying process. As with conditioning, more research on the mechanics of faecal sludge drying is required to generate a fundamental understanding of the process and to inform the development and adaptation of well-functioning drying processes.

4.4.3 Types and mechanisms of thermal drying (technical background)

Understanding the underlying physical, chemical, and biological processes supporting a technology is crucial for making informed decisions about adapting it to work with faecal sludge. During thermal drying,

heat is transferred to the sludge from a heating source (e.g. hot fluid, heated wall, infrared radiation) or generated internally after conversion of another form of energy (e.g. microwave, dielectric radiation), leading to the movement of moisture to the sludge surface where it evaporates. The rate of drying depends on the temperature or irradiance from the heat source, humidity, flow rate, and pressure of the ambient air, and on the area, thickness, and thermal properties (*i.e.* heat capacity and thermal conductivity) of the exposed sludge surface. A schematic representation of heat drying of faecal sludge is shown in Figure 4.14.

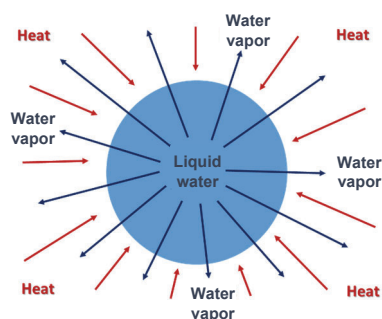


Figure 4.14 Schematic representation of drying faecal sludge. Red arrows represent heat transfer, blue arrows represent mass transfer of water (H_2O).

The most common way to classify thermal drying technologies is according to the heat transfer mode, which are convection (convective drying), conduction (contact drying), and radiation (radiative drying). Convective drying (or direct drying) works by passing hot air or gases directly through the sludge. Contact drying (or indirect drying) instead uses heat exchangers to heat a surface that the sludge is in contact with. Radiative drying provides the heat for moisture evaporation by solar, infrared, microwave, or dielectric radiation. Different types of drying modes can be combined for a given technology. Most drying

systems include a ventilation or vacuum system to evacuate the evaporated moisture and avoid saturation of the air, which can inhibit the drying process. In passive drying systems such as drying beds, the sun and wind provide heat and air flow to promote evaporation. For more detailed information about drying mechanisms or types of industrial dryers used in other fields see Mujumdar (2014). Examples of convective, contact, and radiative drying technologies that have been used with faecal sludge at pilot- and laboratory-scales are presented in figures 4.15 to 4.18.

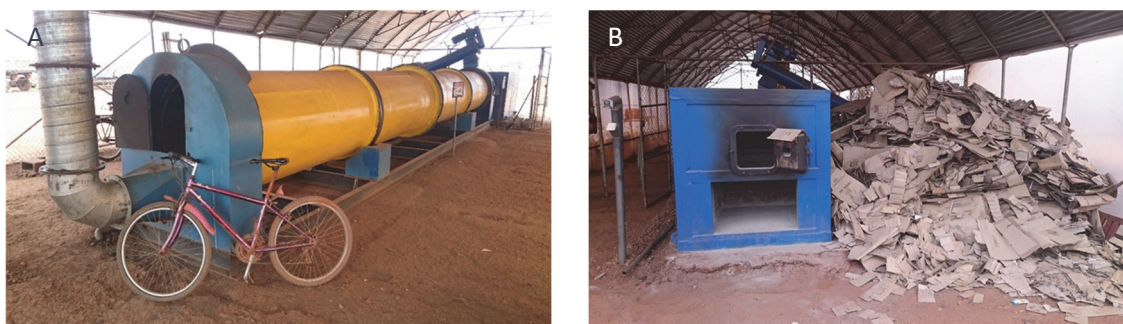


Figure 4.15 A) a rotary convection dryer operated by Pivot, in Kigali, Rwanda and B) waste cardboard is burned in a boiler and the hot gases produced are used as the heat source for drying. The sludge is pre-dried by a solar dryer before entering the convective dryer pictured here (photos: UKZN PRG).



Figure 4.16 A) a contact dryer at the Omni-processor pilot plant at Niayes FSTP in Dakar, Senegal. In this plant, the sludge is incinerated leading to the generation of heat and electricity. B) part of the heat from combustion is recirculated in the process for the drying of the sludge with this contact dryer unit (photos: UKZN PRG).

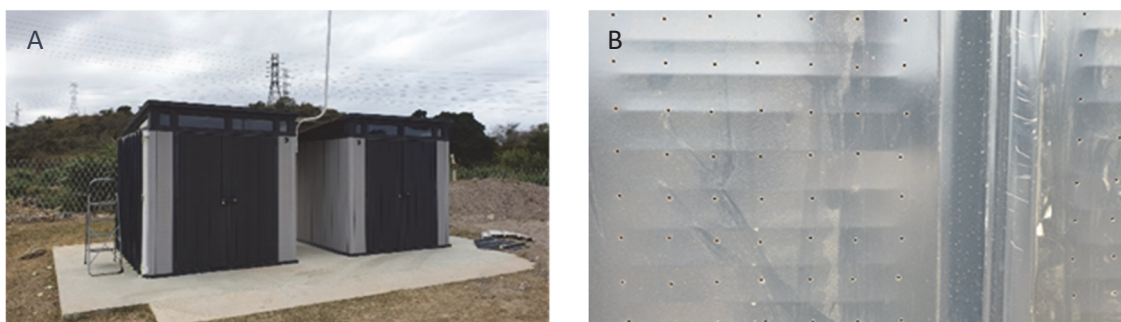


Figure 4.17 A pilot-scale solar dryer developed by Swansea University and tested in Durban, South Africa. A) sludge is placed inside these sheds to dry. B) the walls of the sheds absorb solar energy and transfer it to the sludge inside through a ventilation system (photos: UKZN PRG).

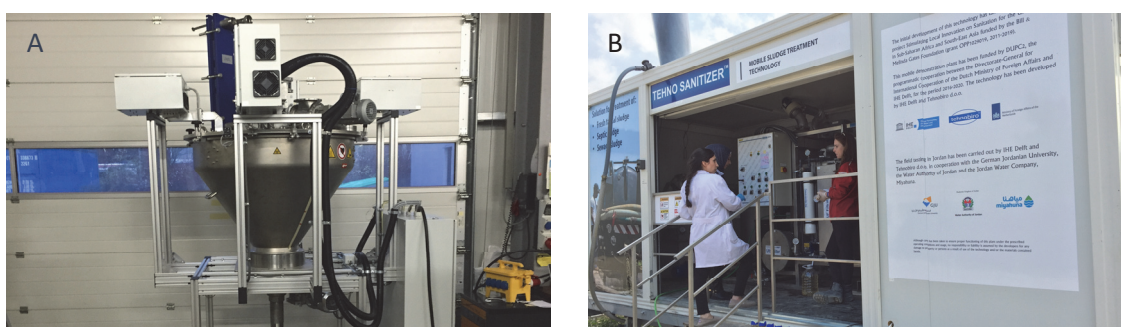


Figure 4.18 A) the bench-scale Shit Killer microwave-based technology for sludge treatment developed by IHE Delft and Fricke und Mallah Microwave Technology GmbH, and B) the follow-up prototype – the pilot-scale Tehno Sanitizer developed by IHE Delft and Tehnobi d.o.o. (photos: IHE Delft).

4.4.4 Key parameters when implementing thermal-drying technologies

When designing or implementing a drying technology, first the amount of time it takes the sludge to dry to the desired moisture content (*i.e.* the drying rate) needs to be determined, along with the amount of required energy. Optimal combinations of key process parameters will yield dry sludge with the desired moisture content at the lowest energy cost. Methods such as pre-treatment of the sludge with stirring, or techniques to enhance the heat and mass transfer such as mechanical vibrations or ultrasound can also be investigated to improve drying performance. The following factors will influence the drying rate and energy consumption of the faecal sludge drying process, and need to be taken into

account during technology transfer and process optimisation (Septien *et al.*, 2018a):

- Intensity of the energy source used to heat the sludge influences the evaporation, heat and mass transfer rates, and energy consumption. Examples of how this is measured are air temperature for convective drying; temperature of the heated surface for contact drying; and irradiance of the radiation source for radiative drying.
- Residence time of sludge in the dryer influences the energy consumption and the final moisture content of the treated sludge. Optimal residence time is used to design for capacity of specific treatment technologies.
- Relative humidity and flow rate of the air stream influence the heat and mass transfer kinetics.

Faster air flow and lower relative humidity promote faster and more complete evaporation, but also often require higher energy input.

- Physical, chemical and physico-chemical characteristics of the faecal sludge influence how much moisture needs to be removed, for example different starting moisture contents and water-binding characteristics, which influence the required energy to remove moisture.
- Sludge volume and geometry influence the rates of heat and mass transfer during drying, for example pellets, bulk sludge, thin or thick layers. Configurations with a higher sludge surface area to volume ratio, such as pellets, promote faster drying, whereas thick layers of bulk sludge require more time.

4.4.5 Laboratory-scale and pilot-scale testing

Laboratory- and pilot-scale testing of drying needs to consider comparable drying temperatures, air-flow rates, energy sources, and humidity ranges to the pilot- and full-scale technologies. Pilot-scale testing should replicate full-scale conditions as closely as possible, using knowledge of scientific mechanisms to evaluate performance for scaling-up. For example, a pilot-scale drying technology should produce pellets of the same size and aspect ratio as the full-scale system.

As mentioned in the previous section, the performance of the drying process at any scale is measured through the evolution of the faecal sludge moisture content as a function of time. In an experimental setup, this can be done through different methods:

- Online or intermittent measurement of the mass of the sample over time, assuming that the mass loss is exclusively due to moisture removal.
- Measurement of the moisture content after sampling a fraction of the sludge at a given time interval.
- Online or intermittent measurement of the humidity at the air-flow outlet, assuming that the gain of humidity in the air is due to moisture evaporation.

The determination of the drying rate under different conditions enables a better understanding of the process, and facilitates the development of kinetic models that can be used as tools for the design, operation and optimisation of drying technologies. Drying kinetics can be characterised at the laboratory-scale using commercially available instruments or custom-designed drying rigs. The commercially available thermogravimetric analyser (TGA) offers high-precision mass measurement during the thermal decomposition of materials, under controlled conditions. It can be coupled to a differential thermal analysis (DTA) or differential scanning calorimetry (DSC) unit, in order to determine the heat released or consumed during the transformation of the material. The main drawbacks of this method are the high cost of the TGA and DSC instruments, and the low sample weight that has to be used in experiments (*i.e.* milligrams), which can lead to reproducibility problems due to the heterogeneity of faecal sludge. The moisture analyser is a more affordable commercial instrument that can record the loss of mass of the sludge during drying. In this device, the sludge is heated by an infrared radiator and a ventilation system evacuates the evaporated moisture. A larger amount of sample can also be used (*i.e.* grams). However, the drying conditions cannot be controlled as well as in the TGA. Custom-designed drying rigs can be adjusted in size and complexity according to the needs and means of the experimenter, and can give a more tailored representation of the drying kinetics of a specific technology. Custom rigs can be as simple as a conventional oven where sludge is occasionally removed to track the mass loss, or a sophisticated experimental rig with high levels of instrumentation and an interface to log the data. Provided in Case study 4.3 is an account of the use of a custom experimental rig to measure faecal sludge drying kinetics under variable process settings.

The physical and chemical changes that the sludge undergoes during drying must be characterised in order to have a deeper understanding of the drying process. Periodic characterisation of the sludge properties during drying also helps researchers to target drying processes to produce suitable end products. The properties of the dried sludge can be quantified with the methods described in Chapter 8:

- Total solids of dried sludge; measured gravimetrically by sludge weight before and after complete drying in a 105 °C oven.
- Calorific value is a measure of energy density, and is measured using a bomb calorimeter.
- Ash and volatile solids content of the sludge are measured gravimetrically with a 550 °C muffle furnace.
- Rheological properties, such as shear stress and viscosity under different shear rates, are measured with a rheometer or viscometer.
- *E. coli* or Helminth eggs can be monitored as indicator organisms for pathogen inactivation, if the end product is required to be pathogen-free.

4.4.6 Case studies - thermal drying for energy recovery

The following three case studies provide examples of (i) how to get useful kinetics data from laboratory-scale devices for the design and development of pilot-scale and full-scale dryers, (ii) how to optimise the performance of a full-scale drying process using experiments conducted with a laboratory-scale apparatus, and (iii) how to optimise the performance of a full-scale drying process using experiments conducted at full-scale.

Case study 4.3 Determination of faecal sludge drying kinetics with a custom-designed experimental rig

This case study presents an example of how to determine faecal sludge drying kinetics in a laboratory-scale custom-designed experimental rig. This investigation was carried out by the Pollution Research Group (PRG) at the University of KwaZulu-Natal (UKZN) in Durban, South Africa. It was part of a MScEng project to learn about the rate at which pit latrine faecal sludge dries under different operating conditions (Makununika, 2017). A rig was custom-designed to study drying rates under different operational conditions in a convective dryer. In this rig, faecal sludge pellets were dried with hot air while their mass loss due to evaporation was measured in real time. The determination of the drying rates will aid in the development of drying technologies suitable for faecal sludge. Determination of kinetic data is an important step towards the design, development, optimisation and scaling-up of drying technologies. It

provides information that is used to size the dryer, to determine the optimum operating conditions, to fix the residence time (continuous mode) or holding time (batch mode), and to estimate the power consumption of the process.

Research question

What is the rate of faecal sludge drying with varying temperature, humidity, air velocity, and pellet diameter?

Response variable

Change in moisture content over time was characterised gravimetrically by a custom-designed convective drying rig. A photograph and schematic representation of the convective drying rig are presented in Figure 4.19.

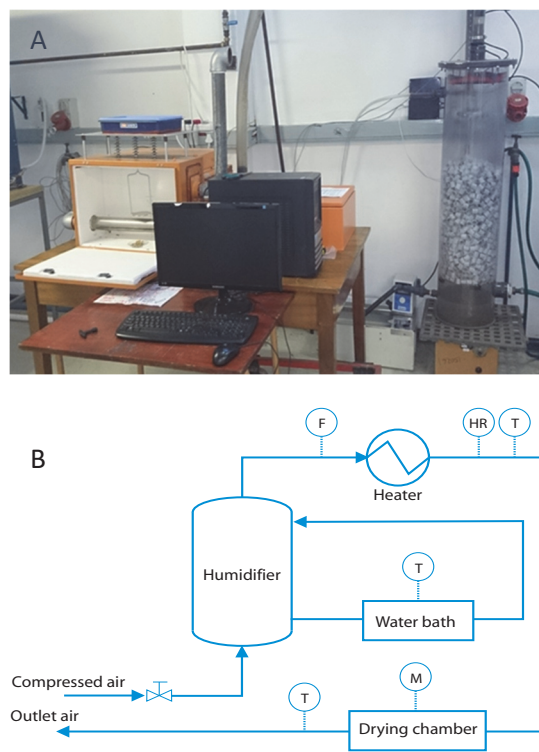


Figure 4.19 A) the custom-designed convective drying rig (photo: UKZN PRG) and B) a schematic representation of the convective drying rig, F: air-flow measurement; T: temperature measurement; M: mass measurement; HR: relative humidity measurement.

During the experiments, dehumidified compressed air was fed into the drying rig. The air-flow rate was measured by a differential pressure measurement device and was controlled by a globe valve. The air stream was humidified in a packed column by counter-current contact with a water flow. The relative humidity of the air was adjusted by controlling the water temperature. The humidified air then passed through an electric heater to raise its temperature to the set value. The hot air stream was then introduced into the drying chamber where the faecal sludge sample was placed on a sample holder linked to a precision weighing strain gauge load cell with an accuracy of 0.01 g. The sample mass was measured online to track the change in mass with time. The air temperature and relative humidity were monitored at the inlet and outlet of the drying chamber. All the measurements were continually logged on a computer.

Factors, levels, and ranges

- Temperature: 40, 60, and 80 °C
- Relative humidity: 5, 15, and 25%
- Air velocity: 0.1, 0.2, and 0.4 m/h
- Pellet diameter: 8, 10, 12, and 14 mm

Factors that might influence the response variable

- Presence of solid waste: faecal sludge can contain considerable amounts of rubbish that can cause interferences and clogging during the drying experiments. In order to avoid this, the sludge samples were screened prior to the experiments, and large pieces of rubbish were removed.
- Heterogeneity of faecal sludge: faecal sludge is highly heterogeneous, which can lead to inconsistent experimental results. In order to reduce heterogeneity and ensure repeatability, the sludge samples were thoroughly mixed prior to the experiments.

Experimental design details

Each run was performed in triplicate. Table 4.2 displays the runs performed in this study from all the possible runs. If all the possible combinations of the selected factors, levels, and ranges had been tested, 108 different runs would have been required. However, this was not feasible in terms of time and

resources, therefore the most appropriate combination of runs was selected in order to study the influence of each variable. This was done by varying the value of a single variable while keeping the others constant at a reference value.

Table 4.2 Matrix with the different runs performed (marked with the symbol ■) out of all the possible combinations.

Temperature (°C)	Relative humidity (%)	Air velocity (m/h)	Pellet diameter (mm)			
			8	10	12	14
40	5	0.1	■	■		
		0.2		■		
		0.4		■		
	15	0.1		■		
		0.2				
		0.4				
	25	0.1		■		
		0.2				
		0.4				
60	5	0.1	■		■	■
		0.2				
		0.4				
	15	0.1				
		0.2				
		0.4				
	25	0.1				
		0.2				
		0.4				
80	5	0.1	■			
		0.2				
		0.4				
	15	0.1				
		0.2				
		0.4				
	25	0.1				
		0.2				
		0.4				

Interpreting the results

The results of the experiment are presented in Figure 4.20.

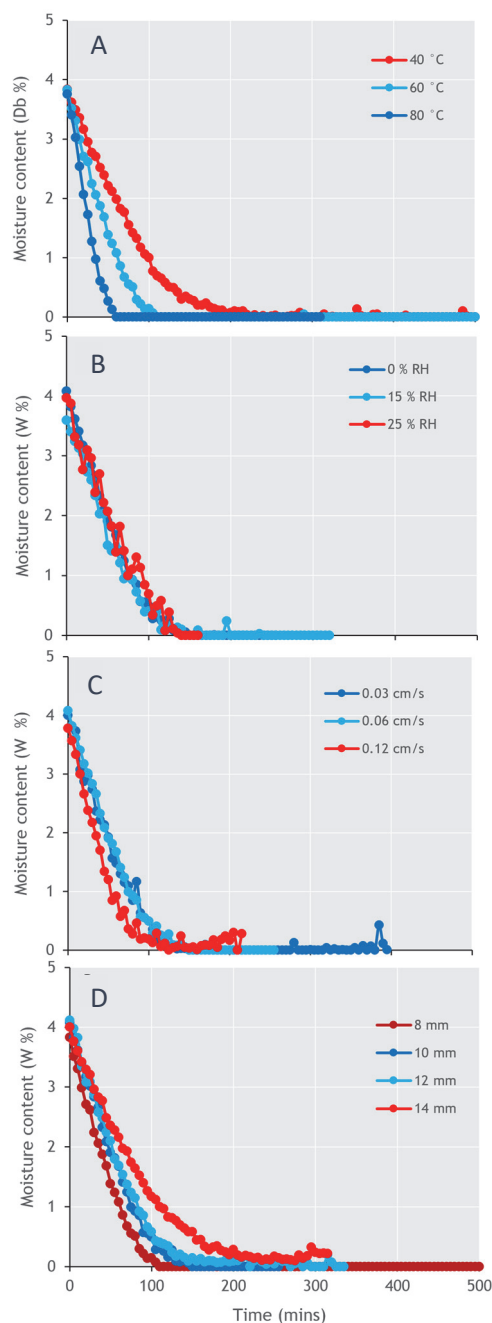


Figure 4.20 A) Drying rate as a function of air temperature, B) relative humidity, C) air velocity, and D) pellet diameter.

The main findings of this study were:

- Air temperature has a major influence on the drying rate. Increasing the temperature from 40 to 80 °C decreased the drying time from 3 hours to 1 hour.
- The diameter of the sludge pellets also has an important influence on the drying rate. The 8 mm pellets were completely dried within 100 minutes, whereas the 14 mm pellets required drying times greater than 200 minutes.
- The relative humidity and air velocity had low or negligible influence on the drying kinetics under the explored conditions.

Scaling-up from laboratory to pilot-scale

According to the experimental results in this case study, the most critical parameters to optimise during drying are the air temperature and diameter of the sludge pellets.

The experimental data from this work was used to develop a mathematical model that could be inserted into reactor models as a tool for simulation to design new dryers, and can be used in process control for scaled up systems (Makuninika, 2017).

Case study 4.4 Optimising the LaDePa process for infrared faecal sludge drying

This case study is based on a Master's thesis by Simon Mirara (Mirara, 2017). Further information can be found in Septien *et al.*, 2018a, 2018b, and Septien *et al.*, 2020. The motivation for this research project was to optimise the existing full-scale Latrine Dehydration Pasteurisation (LaDePa) process. The LaDePa process was implemented in the eThewini municipality in Durban, South Africa to treat the faecal sludge from ventilated improved pit (VIP) latrines through infrared drying, to produce dry, pathogen-free pellets for use as a soil conditioner or solid fuel. The LaDePa process was developed by the eThewini municipality and Particle Separation Systems as a transferring technology from the mining industry where it was applied for drying of minerals. Based on the treatment performance of the full-scale LaDePa, the municipality decided that it needed to be optimised to minimise energy consumption while maximising the drying rate, pasteurisation performance, and end-

use potential in the treated sludge. In order to optimise drying in the LaDePa process and to develop a deeper understanding of the drying process, a 1:10 laboratory-scale replica of the full-scale LaDePa was constructed (Figure 4.2.1).

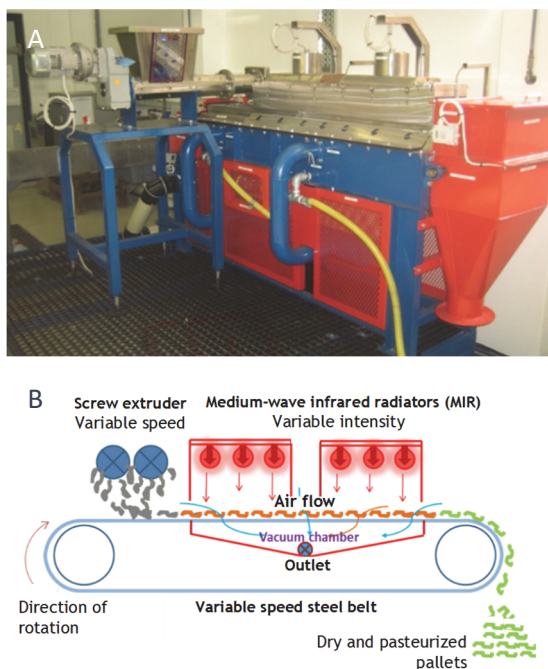


Figure 4.21 A) the laboratory-scale LaDePa, and B) a corresponding schematic representation of the process (photo and schematic: UKZN PRG).

Research question

What process settings for faecal sludge drying with the LaDePa infrared dryer minimise energy consumption and maximise sludge drying rate?

Response variables

The laboratory-scale LaDePa was used to characterise the moisture content of the dried pellets, and energy consumption of the process, at different conditions (see factors, levels and ranges). The sludge was fed into the machine as pellets formed with a screw extruder, which were conveyed by a moving belt under two successive infrared emitters (providing heat for drying). An air stream was induced in the drying

zone through an air suction box system installed below the belt to keep humidity low (Figure 4.21).

The dried pellets after processing were analysed to determine physical, chemical and biological properties, such as moisture content, volatile solids content, nutrient content, calorific value, thermal properties and helminth eggs. The drying and pasteurisation performance of the process were measured through the moisture content evolution and helminth egg viability. The end-use potential of the dried sludge was evaluated through the measurement of their properties.

Factors, levels, and ranges

- Emitter intensity (infrared irradiance): 6, 24, and 34 kW/m².
- Residence time: 4, 8, 12, 17, 26, and 39 minutes (varied by adjusting the speed of the belt).
- Distance between the belt and infrared emitters: 50, 80 and 115 mm (varied by adjusting the belt height).
- Suction air-flow rate: 11.1 and 18.3 m³/s.
- Pellet diameter: 8, 10, 12 and 14 mm.

Factors that might influence the response variables

- Heterogeneity of sludge and presence of solid waste: as in Case Study 4.3, large pieces of solid waste were screened and removed from the sludge, and screened sludge samples were thoroughly homogenised prior to experimentation.
- Ambient temperature and humidity: ambient air is used for ventilation in the LaDePa, thus, the temperature and humidity of the suction air stream is dependent on ambient conditions. As the laboratory is climate-controlled, the ambient conditions are quite steady throughout the year and it was assumed that these parameters did not significantly change throughout the course of the study.
- Loading density of the pellets on the belt: this could have an influence on the performance of the process, as it could be expected that the drying of large sample loads would require a higher heat input. To address this, the loading density on the belt was kept consistently low in this investigation. Prior to scaling-up, higher loadings will be investigated.

Experimental design details

Due to available time and resources, the following runs, indicated with a ■ in Table 4.3, were determined to be the most relevant.

Table 4.3 Matrix with the different runs performed (the most relevant marked with ■) out of all the possible combinations.

Emitter irradiance (kW/m ²)	Height emitter (mm)	Air-flow rate (m ³ /h)	Pellet diameter (mm)			
			8	10	12	14
6	50	11.1				
		18.1	■			
	80	11.1				
		18.1				
24	50	11.1				
		18.1	■	■	■	■
	80	11.1				
		18.1	■			
34	50	11.1				
		18.1	■			
	80	11.1				
		18.1				
34	115	11.1				
		18.1				

Interpreting the results

Results of the experiment are presented in Figure 4.22.

As expected, the rate of drying increased as the intensity of the infrared radiation increased and the distance between the pellets and the heating source decreased. Drying was faster for pellets with a smaller diameter. Increasing the suction air-flow rate caused a cooling effect on the sludge (negative for the process) but also enhanced the evacuation of moisture from the surface of the pellets (positive for the process). Under the explored conditions, these opposing effects counteracted each other and the overall drying rate

was not affected by changing the air-flow rate. The pre-treatment of the sludge also did not affect the drying rate.

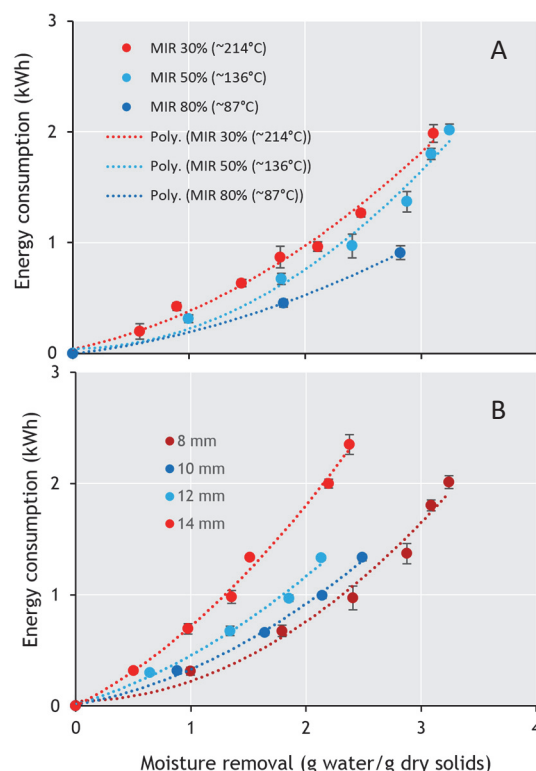


Figure 4.22 A) Plot of moisture removal vs energy consumption at varied medium-wave infrared intensities (MIR). MIR of 30, 50 and 80% equals infrared irradiance of 6, 24, and 34 kW/m², respectively, and B) plot of moisture removal vs energy consumption at varied pellet diameters.

The energy consumption for moisture removal was determined from the kinetic data. Depicted in Figure 4.22, the drying process consumes less energy to remove a given amount of moisture when operating at higher infrared heating intensity and with smaller diameter pellets. However, it was observed that drying at too high a heating flux could induce thermal degradation of the sludge, which could lead to charring or burning. During the trials, drying at the highest infrared intensity (34 kW/m²) resulted in the pellets starting to smoke.

Process optimisation from laboratory- to full-scale

Based on the results of the laboratory-scale experiments, it is recommended to operate the LaDePa at the highest possible infrared radiation intensity that does not cause thermal degradation. During laboratory tests, in addition to monitoring energy consumption and drying time, helminth egg viability and net calorific value were measured. During tests, full deactivation of helminth eggs was achieved. It is not recommended to operate at the highest intensity setting, as the resulting thermal degradation could reduce the suitability of the dried sludge for reuse as a solid fuel. The distance between the infrared emitters and the belts should be minimised, in order to maximise the amount of radiation received by the pellets without the need of an increased power supply. Implementing these results will result in lower energy use and operating costs.

The faecal sludge should also be pelletised at the lowest diameter possible for a more efficient drying process. This will require experimentation with the full-scale extruder to determine the smallest diameter achievable at scale. After process changes are made, pellets produced at full-scale will need to be further evaluated for pathogens to ensure protection of public health during the end use. ■

4.5 TRANSFERRING TECHNOLOGY: MICROWAVE DRYING FOR RESOURCE RECOVERY OF DRIED SLUDGE FOR ENERGY

Microwave drying is a type of radiative drying where microwave radiation is used to heat the sludge. In the microwave drying process, microwave radiation heats the core of the sludge particles promoting the transport of water molecules from the inside to the surface; this results in a large amount of water molecules at the surface of the sludge that can be more easily evaporated compared to the water bound deeper within sludge particles. Due in part to this mechanism, microwave drying can offer energy savings compared to other thermal drying technologies.

Case study 4.5 Optimising the Tehno Sanitizer technology for microwave faecal sludge sanitisation and drying

This case study is based on two PhD and several MSc studies carried out at IHE Delft Institute for Water Education in The Netherlands (IHE Delft). It concerns the development of a novel microwave-based technology for sludge sanitisation and drying. The new technology is an example of a development that has passed through all the Technology Readiness Levels (TRLs) (Héder M. 2017), starting from a small laboratory-scale setup using an adapted kitchen microwave (Mawioo *et al.*, 2016a; Mawioo *et al.*, 2016b), to a bench-scale unit (Mawioo *et al.*, 2017) and finally, to a full-scale prototype (Kocbek *et al.*, 2020, in preparation). This technology, called the Shit Killer, was initially developed for decentralised faecal sludge treatment in emergency sanitation (Brdjanovic *et al.*, 2015) and has evolved into a robust and efficient technology known nowadays as the Tehno Sanitizer (Figure 4.23). The Tehno Sanitizer prototype, recently tested in Jordan, is equipped with four technologically-independent but inter-connected functional components, namely: (i) microwave-based sludge treatment, (ii) liquid stream treatment, (iii) air treatment, and (iv) an energy-recovery system (Figure 4.23).

The bench-scale Shit Killer unit was successfully tested for pathogen removal and sludge drying in Slovenia. At that time, the specific energy consumption (SEC) (energy consumed per liter of evaporated water) was not the primary objective and thus was, as expected, sub-optimal. The main reasons for this were: (i) lack of thermal insulation, (ii) inefficient use of microwave energy, (iii) less efficient mixing at higher sludge densities, (iv) cold ambient temperature (5 °C), (v) poor extraction of the condensate from the cavity, (vi) unnecessary heating of the cavity, and (vii) absence of energy recovery features.

All of these shortcomings have been addressed and mitigated in the next generation full-scale prototype: the Tehno Sanitizer. This system is a semi-decentralised and containerised mobile full-scale prototype designed for the treatment (drying, pathogen inactivation, and resource recovery) of diverse types of sludges such as fresh faecal sludge