2

Faecal sludge properties and considerations for characterisation

Konstantina Velkushanova
Linda Strande

OBJECTIVES

The objectives of this chapter are to:

- Present four types of faecal sludge depending on total solids content
- Provide a brief overview of factors that can influence characteristics of faecal sludge along the service chain.
- Explain the relevance of selecting different faecal sludge properties based on the objectives of characterisation
- Explain factors for consideration when selecting characterisation methods
- Provide guidelines for setting up faecal sludge laboratories, along with case studies of existing implementations

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2.1 INTRODUCTION

Faecal sludge characterisation is the process of measuring and evaluating faecal sludge properties. The characterisation of faecal sludge as a material, and understanding the nature of the physical, biological, and chemical characteristics, is necessary for the research, design, implementation, and operation of faecal sludge management solutions. Common reasons for characterising faecal sludge include understanding biochemical processes of degradation and nutrient cycling, monitoring of treatment efficiency and pathogen removal, determining loadings for the design and operation of a treatment plant, selecting the best technology for emptying of sludge from onsite containments, and evaluating the potential for resource recovery. Based on the defined purpose and objectives of the faecal sludge characterisation, the appropriate methods for measurement of properties need to be selected.

However, defining standardised methods for the characterisation of faecal sludge is challenging due to the high variability of faecal sludge, from the micro- to the macro-scale. In addition to the variability, different methods for sample preparation and analysis are appropriate depending on the 'type' of faecal sludge. For example, samples with higher total solids (TS) content and lower moisture content from 'dry' systems, such as pit latrines, urine-diverting dehydration toilets (UDDTs) and composting toilets, will likely require a different preparation than samples collected from 'wet' systems, such as septic tanks, 'wet' pit latrines, and cesspits that have much lower TS content. The solids content will also affect whether it is relevant to conduct volumetric analysis (*e.g.* milligram of constituent per litre of the sample) or gravimetric (*e.g.* gram constituent per gram TS of the sample). Other complicating factors for standardisation include a wide range of available resources, equipment, and capacity of laboratories. This chapter presents background information that is necessary to understand prior to the use of the methods presented in Chapter 8. It defines types of faecal sludge based on TS concentration, which is necessary for implementing the correct steps in the methods. It introduces factors that affect the variability of characteristics along the entire service chain in order to understand what analyses are relevant. It then provides guidance on how to select appropriate methods for characterisation, based on several criteria such as characterisation objectives, relevant characteristics, desired level of accuracy, laboratory capacity, and available resources. The chapter then presents considerations specific to the characterisation of faecal sludge for setting up a faecal sludge analytical laboratory, and includes four case study examples of how operational laboratories can look when implementing all of the steps presented in this chapter.

2.2 TYPES OF FAECAL SLUDGE

Faecal sludge is highly variable based on its broad definition and decentralised nature, as faecal sludge is anything and everything that is collected and accumulated within containment technologies of onsite sanitation systems (Chapter 1). Qualitative observations of different moisture or TS content of faecal sludge range from dilute and watery, to slurries that are still pumpable, to dewatered sludge that is 'shovelable' or 'spadable'. Although these differences do not have clear boundaries that can be precisely defined, it is useful to define approximate ranges of types of faecal sludge based on TS. The different ranges can have an impact on which methods of analysis and sample preparation are applicable, and also if concentrations are analysed and reported by volumetric or gravimetric concentration. Below are the four types of faecal sludge based on TS concentration.

- *Liquid faecal sludge*
  TS <5%, runny liquid, relatively dilute with the consistency of water or domestic wastewater, readily pumpable. Usually collected from 'wet' containments such as leach pits and septic tanks, or 'wet' pit latrines.
- *Slurry faecal sludge*
  TS 5-15%, thicker than liquid, but still runny, from watery to wet mud consistency, pumpable in the lower range, too runny to shovel, and not spadable. Common in pit latrines (improved or unimproved) with a frequent input of greywater or due to infiltration. Can also be collected from the bottom of septic tanks and leach pits.

- *Semi-solid faecal sludge*
  TS 15-25%, soft paste-like, not pumpable, at the higher range can be spadable, is collected from onsite containments such as pit latrines, composting toilets, and leach pits, or from dewatering treatment technologies.

- *Solid faecal sludge*
  TS >25%: The majority of free water has been removed, can come from dry toilet systems or dewatering treatment technologies. For more details on free water, bound water, and dewatering, refer to Chapter 4.

If TS measurements are taken volumetrically (*e.g.* g/L), then they need to be converted to % as TS. This can easily be done using the density of samples. For example, if a sample with 10 g TS/L faecal sludge has the density of water, then it is equivalent to 1% TS. In this way gravimetric measurements can also be converted to volumetric. When doing such conversions, it is always recommended to measure the actual density of the specific samples, and this becomes even more important with samples at the higher range of % TS.

$$\underbrace{\left(\frac{10\text{ gTS}}{\text{L}_{\text{sample}}}\right)}_{\text{Volumetric measurement}}\cdot\underbrace{\left(\frac{\text{m}^3}{1{,}000\text{ kg}}\right)}_{\text{Water density}}\cdot\underbrace{\left(\frac{1{,}000\text{ L}}{\text{m}^3}\right)\cdot\left(\frac{\text{kg}}{1{,}000\text{ g}}\right)}_{\text{Conversion units}}$$

$$=\frac{10\text{ gTS}}{1{,}000\text{ g}_{\text{ sample}}}=\underbrace{\frac{1\text{ gTS}}{100\text{ g}_{\text{ sample}}}}_{\text{Gravimetric equivalent}}=1\%\text{ TS}$$

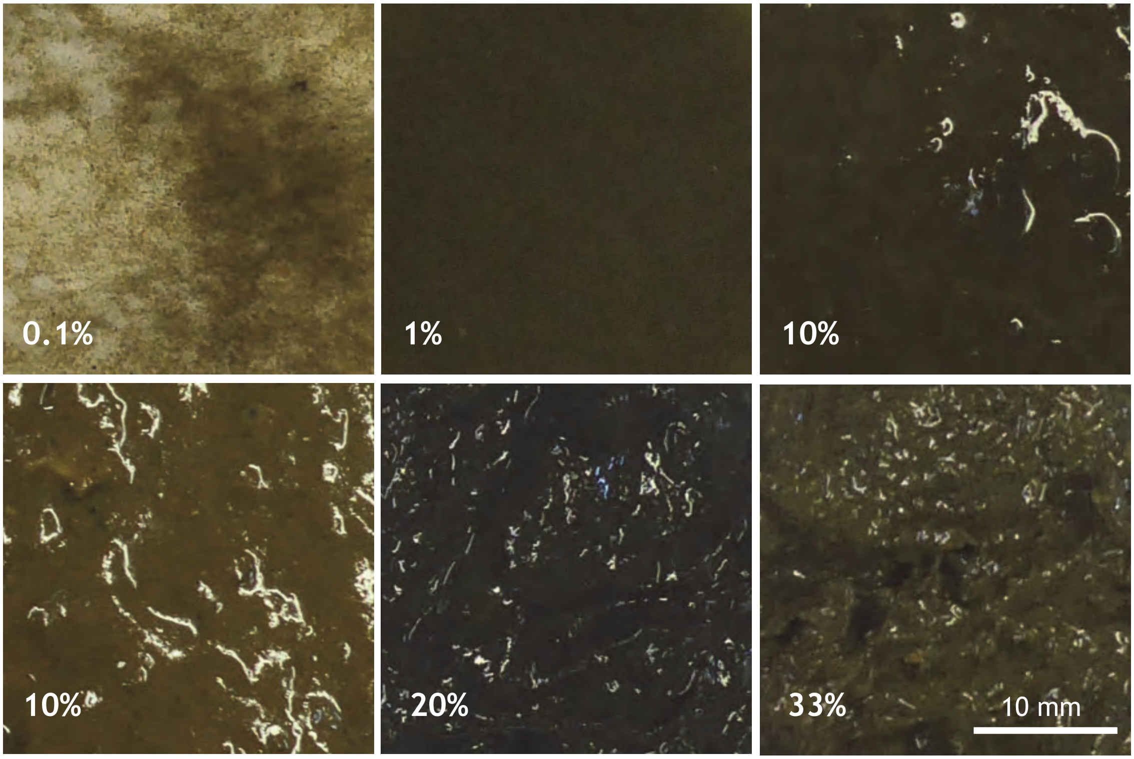

Figure 2.1 Example photos of 10 mL samples of faecal sludge in Petri dishes, in the four different types of faecal sludge by TS concentration: liquid, slurry, semi-solid, and solid. The scale bar is included for reference (Ward *et al.*, 2021).

Presented in Figure 2.1 are examples of what faecal sludge can look like at different TS content. The pictures were taken of 10 mL samples of faecal sludge in a Petri dish, during a study in Lusaka, Zambia (Ward *et al.,* 2021). The samples were collected *in situ* from onsite containments, and have not been treated. In the picture of the 0.1% TS faecal sludge, it is apparent that the sample is fairly dilute. In the 1% TS sample, the colour is more consistent but the texture is still watery. With the 10-33% TS samples there is increasing texture as the solids become more concentrated. In contrast, the appearance is quite different with solid to semi-solid sludge following dewatering (see Figure 2.10 for comparison). It is important to note that although the liquid, slurry, semi-solid, and solid types of faecal sludge are defined by their TS concentration, all the other characteristics do not follow the same trend, and need to be grouped independently. For example, level of stabilisation, or ammonia (NH_3) nitrogen concentration, could be relatively high or relatively low in any of the pictured samples. This is illustrated by the similar texture but difference in colour between the two samples with 10% TS, which is an indication of their differing levels of stabilisation.

2.3 FACTORS INFLUENCING THE FAECAL SLUDGE CHARACTERISTICS ALONG THE SANITATION SERVICE CHAIN

Faecal sludge in general consists of excreta, anal cleansing material, flushwater, greywater, chemicals, and solid waste, in addition to anything else that can end up in the containment, all of which are referred to as ‘inputs’ to faecal sludge. The diverse practices of individual households, communities, and the commercial sector contribute to the variability of characteristics and volumes of produced, accumulated, and collected faecal sludge. In addition, a wide range of factors along the entire service chain influence the faecal sludge characteristics in a multitude of different ways (Figure 2.2).

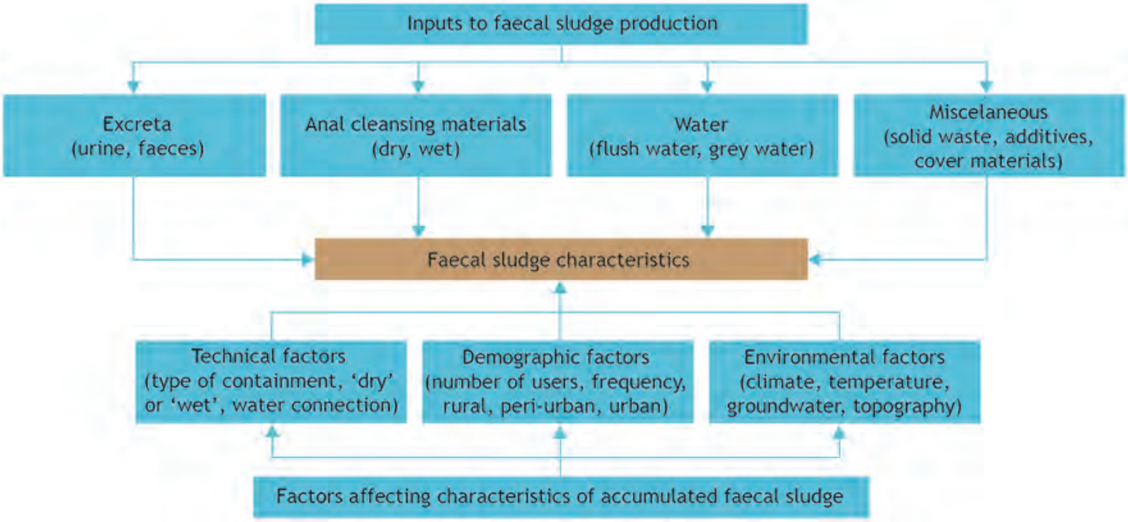

Figure 2.2 Illustration of the inputs to faecal sludge described in Section 2.3.1, and different technical, demographic, and environmental factors affecting and modifying the characteristics of faecal sludge in onsite containment, as described in Section 2.3.2.

What happens during onsite storage of faecal sludge in containment is a complex system. With the current state of knowledge, it cannot be said exactly what the role of each factor is since they are all interrelated. How to start developing this level of knowledge is the topic of Chapter 6, which is focused on developing models of what is occurring at the micro-scale within containment. The important distinction between what is produced versus what actually accumulates in containment is discussed in more detail in Chapter 5. Presented in this section is a brief overview of the overall influence that different factors can have on the diversity of faecal sludge characteristics along the service chain that should be taken into account when determining relevant properties to characterise, together with sampling plans. For specific examples from the literature of the range of reported values of characteristics, the reader is referred to the link of a database provided in Annex 2, open source values for 240 samples in Hanoi and Kampala[1], and the following textbooks: Strande *et al.* (2014), Robbins and Legon (2014), Tayler (2018), and Englund and Strande (2019).

2.3.1 Inputs to faecal sludge production

The first step in the sanitation service chain is the user interface (*e.g.* toilet of any design), which is connected to the onsite containment. In addition to excreta, anal cleansing materials and potentially flushwater, other inputs to the containment can include greywater, solid waste, cover material, and chemicals, as explained in the following sections.

2.3.1.1 Excreta

Excreta consists of urine and faeces that have not been mixed with flushwater, and together are considered to be highly concentrated in both nutrients and pathogens (Tilley *et al*., 2014, Figure 1.2). Excreta are either collected as mixed urine and faeces, or separately using urine diversion (UD) toilets, with or without the use of flushwater. The amount of urine per person per year ranges from 300 to 550 L/cap.yr, depending on factors such as liquid intake and sweat production (Rose *et al*., 2015). Yearly production of urine contains 2 to 4 kg of nitrogen depending on the local diet (Tilley *et al*., 2014). The proportional contribution of urine to faecal sludge will affect the total nutrients and salts, which continue to have an effect on characteristics throughout the service chain. For example, total NH_3 concentration in faecal sludge greater than 3,000 mg/L inhibits anaerobic digestion processes (Colón *et al*., 2015). The median daily wet mass of faeces produced per person is 128 g, but the reported range is 35-796 g (Rose *et al*., 2015; Zakaria *et al.,* 2018). Factors affecting the characteristics of faeces include pathogens that can cause diarrhoea, and dietary intake, such as fibres (*i.e.* fruits, grains, vegetables, beans), polysaccharide (*i.e.* starch), and lipid (*i.e.* fats and oils) intake. The type and amount of fibre content can reduce the time that faeces spend in the colon, and increase the size of faeces production and water-holding capacity (Stephen and Cummings, 1979; Stasse-Wolthuis *et al*., 1980). Although diet has an effect on faeces composition, the overall effect of diet and health on the characteristics of the resulting faecal sludge that accumulates over time in containment has not yet been studied. Detailed information on the chemical and physical properties of faeces and urine are presented in Chapter 7.

2.3.1.2 Water inputs

In some toilet systems, flushwater is used to transport excreta to the containment. The volume of flush depends on the type, there are no standard volumes, but in general the volume increases in the order pour-flush (0.5 L), low-flush (1-2 L), and cistern-flush (6-9 L), with modern versions of cistern-flush as low as 3 L, and older versions of cistern flush going all the way up to 20 L. The mix of excreta, anal-cleansing materials and flushwater that is transported to the containment is called blackwater. If the urine and faeces are collected and/or flushed separately in urine diversion toilets for example, then they are referred to as yellow water and brown water, respectively (Tilley *et al*., 2014). Additional inputs of water into containment include greywater from food preparation, cleansing, and bathing. Greywater can also contain pathogens from washing diapers, dirty clothes, or food (Gross *et al*., 2015).

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[1] https://doi.org/10.25678/0000tt

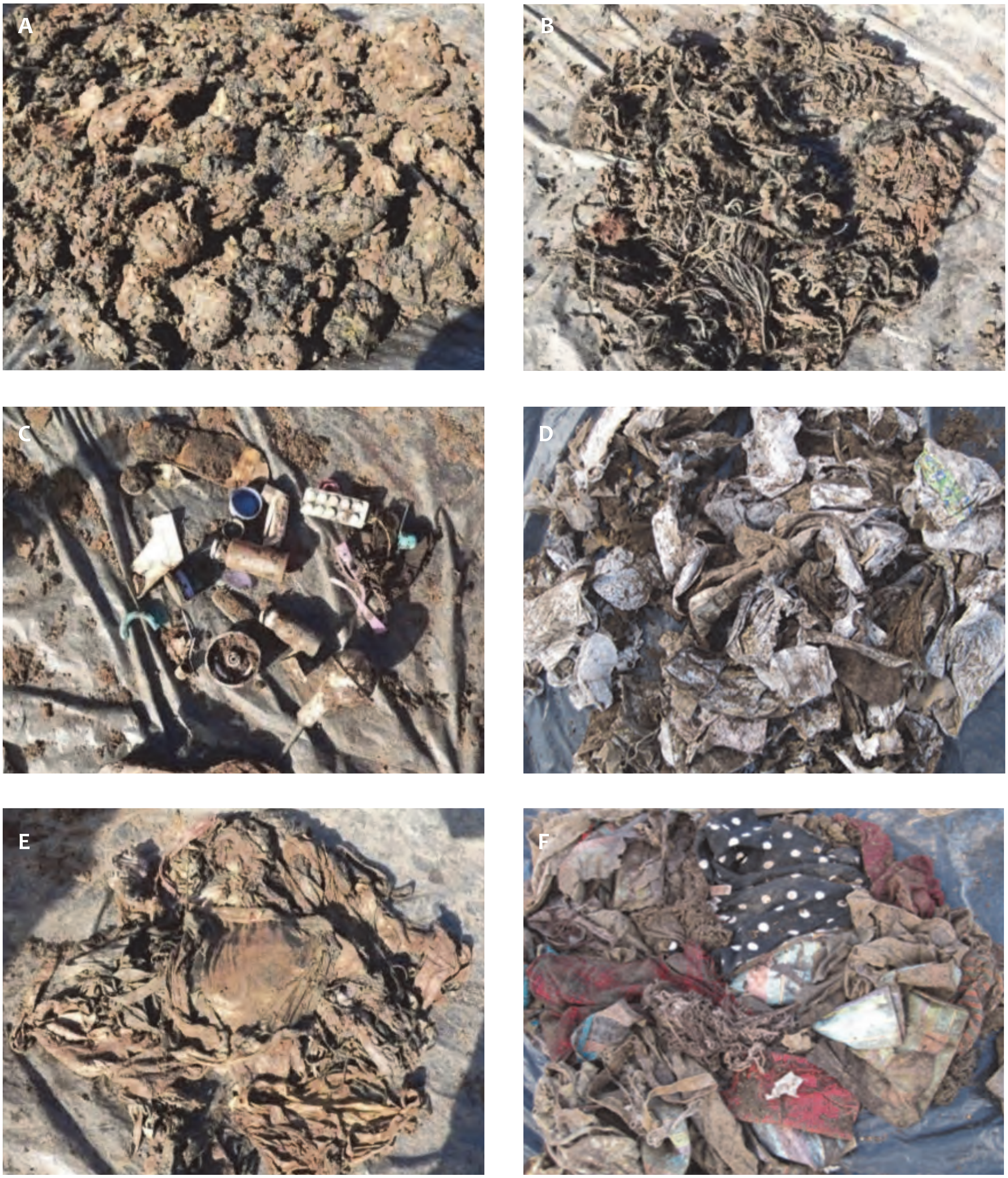

Figure 2.3 Solid waste materials removed from onsite containments in Durban, South Africa: A) paper, B) artificial hair, C) rigid plastics, D) menstrual products and nappies, E and F) textiles (A, B, C and E are from ventilated improved pit latrines; D and F are from a standing UDDT vault, not currently in use), (source: UKZN PRG).

In general, water inputs to containment are much larger with increased availability of water. If, for example, households have to collect water at a standpipe they will tend to use much less water than if they have a direct connection to a water supply pipe. This additional influx of water into containments results in a greater volume of liquid faecal sludge being produced. The resulting increased volumes of liquid faecal sludge are more difficult to safely contain and manage, and can result in increased environmental contamination, whether from outflow of tanks, overflowing containments, or leaching. For an example the reader is referred to the published data set associated with Strande *et al*. (2018) and Englund *et al*. (2020).

2.3.1.3 Anal cleansing materials

Liquid or solid anal-cleansing materials are used by individuals to cleanse themselves after defecating and/or urinating. Liquid materials are water or water mixed with cleansing detergents (Zakaria *et al.,* 2018), usually between 0.5 L and 3 L per use (Tilley *et al*., 2014). Solid or dry materials can include toilet paper, newspapers, magazines, leaves, and rags, which can be collected and disposed of in the containment or separately from the toilet system. Depending on the culture of anal cleansing, users are in general categorised as 'washers' using liquid, and 'wipers' using solid materials. The accumulation of anal-cleansing materials can affect the characteristics of the faecal sludge, depending on the additional inputs. For example, wet cleansing can result in a higher water content, and dry cleansing a greater concentration of fibres from paper.

2.3.1.4 Additional inputs

The disposal of materials in containments, such as non-biodegradable solid waste (*e.g.* textiles, rags, plastic bags, paper, broken glass, bottles) and food waste is common practice in many low- and middle-income countries (Ahmed *et al*., 2018). Municipal solid waste management practices also play a role in the amount of solid waste that accumulates in containments. Where affordable solid waste collection exists, there tends to be less waste ending up in the faecal sludge. However, it is difficult to know what is in a containment, without physical removal of the sludge (Bakare *et al*., 2012). The disposal of solid waste into containments (see the pit latrine example in Figure 2.3) can increase the filling rate, reduce the sludge biodegradation rate, and affect the pit emptying process (Zuma *et al*., 2015; Radford *et al*., 2015). Technical factors also play a role, for example there will in general be less solid waste in containment associated with flush toilets such as septic tanks and leach pits, as it is difficult to pass through the water seal syphon (Byrne *et al*., 2017).

Chemical products also find their way into containments in the form of cleaning materials, or additives that are purposely put into the containment in the belief that they can reduce odours or increase degradation (Anderson *et al.,* 2015). However, there is no evidence that additives are effective. On the contrary, evidence shows that it can have negative results such as impeding the biodegradation process, and the accumulation of undesired gases and odours (Buckley *et al*., 2008; Grolle *et al*., 2018; Kemboi *et al*., 2018).

Cover materials such as soil, ash, sawdust, and garden or agricultural waste are often added to dry systems such as composting and urine diversion and dehydration toilets (UDDT) after each use to combat odour and facilitate the composting process (Stenström, 2004).

2.3.2 Factors affecting characteristics of accumulated faecal sludge

What actually accumulates over time in containment is quite different to the inputs into containment. The difference is the result of a number of demographic, environmental, and technical factors, as depicted in Figure 2.2. Reported examples from the literature include: environmental factors such as oxygen, moisture, climate, inflow and infiltration, soil characteristics; technical factors such as the presence of an overflow pipe, the containment design, sludge age, influent organic matter content, hydraulic retention time, non-biodegradable fraction; and demographic factors such as the number of users, and user behaviour (Brouckaert *et al*., 2013; Elmitwalli, 2013; Franceys *et al*., 1992; Gray, 1995; Howard, 2003; Koottatep *et al*., 2012; Lugali *et al*., 2016; Nakagiri *et al*., 2015, Strande *et al*., 2018). Further factors that affect the resulting quantities and qualities (Q&Q) of accumulated faecal sludge are discussed in Section 2.3.2 on emptying and transport, and chapters 5 and 6.

2.3.2.1 Technical factors

Technical factors such as the type and quality of construction, and whether or not systems are dry or wet (Section 2.3.1.2) will play an interrelated role in contributing to the characteristics of accumulated faecal sludge. Since onsite containments are typically located underground, with little to no manufacturing or construction standards or records, it is difficult to figure out exactly how they were constructed. Care has to be taken, as what is commonly referred to in many countries as a 'septic tank' can actually mean something quite different in the local vernacular, and similarly what is meant by a pit latrine or cesspit is also not standardised. This is discussed in more detail in Example 5.1, and types of onsite containment in Tilley *et al*., 2014.

Although no clear definitions can be made, major influences on the characteristics of faecal sludge resulting from different types of containment will have to do with whether they are fully-lined, partially-lined, or unlined, and whether or not there is an overflow. If a containment is fully lined with no outlet, it will likely need to be emptied frequently so the sludge will be more 'fresh' or less stabilised and the accumulated faecal sludge will have a lower TS concentration. If a containment is unlined or partially lined, it will be more influenced by soil and groundwater conditions. In more 'wet' systems that include overflows, depending on emptying frequency, layers will form with higher concentrations of TS in a sludge layer at the bottom, and a scum layer at the top, consisting of fats, oil, and grease.

Dry systems are most commonly a type of pit latrine, whereas wet systems can include pit latrines, septic tanks, or cesspits (Nakagiri *et al*., 2015; Semiyaga *et al*., 2015; Chiposa *et al*., 2017). Logically, faecal sludge from dry toilets tends to have higher TS and chemical oxygen demand (COD) content (*i.e.* slurry to solid) than wet systems, and can develop a thick layer at the bottom that is difficult to empty (Brandberg, 2012; Radford and Fenner, 2013). In some regions, composting toilets and UDDT are also common, with accumulated faecal sludge >20% TS (*i.e.* semi-solid to solid). Since the urine is collected separately, UDDT sludge will also have lower concentrations of nitrogen and salts.

The amount of water going into wet systems will depend on the type of flush (Section 2.3.1.2), if greywater goes to the containment, and access to water. The additional water input to the containment means that faecal sludge from wet systems is more dilute (*i.e.* liquid to slurry) than dry systems. In comparison to sludge from pit latrines, septic tank sludge commonly has lower concentrations of TS and COD (Strande *et al*., 2018; Bassan *et al*., 2013; Nzouebet *et al*., 2015; Englund *et al*., 2020). Faecal sludge with lower TS concentration is more pumpable, which can determine whether or not manual emptying is required (Radford and Fenner, 2013). The level of stabilisation will depend on the emptying frequency, and moisture content will also have an effect on the rates of microbial activity (Byrne *et al*., 2017; Bakare, 2014).

2.3.2.2 Demographic factors

Studies have found significant differences in faecal sludge and wastewater characteristics based on demographic factors such as number of users and income level (Campos and Von Sperling, 1996; Strande *et al*., 2018; Englund *et al*., 2020). Demographic factors may or may not play a direct role in the characteristics of faecal sludge, but can have an indirect effect due to cultural differences, types of dwellings, and land use, for example, septic tanks being located in higher-income areas with more access to household water, and pit latrines in poorer areas with less dilution from greywater (Semiyaga *et al*., 2015; Strande *et al*., 2018). In urban areas, pit latrines typically have more users and more frequent emptying than pit latrines in rural areas (Wagner and Lanoix, 1958). This is due to higher population density, increased number of users per household, and increased use frequency. For example, in Kampala there is an average of 30 users per household level latrine, and 82 people per public toilet latrine (Günther *et al*., 2011). The effect on characteristics can be quite variable, and will also depend on environmental and technical factors.

In addition to faecal sludge that is produced at a household level, it is important to consider sources such as public toilets, restaurants, hotels, schools, hospitals, offices, stores, shopping centres, places of worship, and industrial areas, which will have comparatively different usage patterns. The faecal sludge from restaurants, for example, has a comparatively higher content of fat, oil and grease. Sometimes in establishments with high levels of generated sludge such as commercial areas, hospitals, or industrial areas, the faecal sludge produced is collected in watertight tanks with a very high emptying frequency (Strande *et al*., 2018), but in contrast, in other locations, industrial and commercial areas have been observed to have lower rates of accumulation (Prasad *et al*., 2021). Regardless, the non-household contribution represents a significant fraction of generated faecal sludge, and in urban areas the population can double during the day with people commuting in to the city for work. At the Lubigi faecal sludge treatment plant (FSTP) in Kampala, Uganda, 50% of the faecal sludge was found to originate from non-household sources (Strande *et al*., 2018).

2.3.2.3 Environmental factors

Environmental factors such as climate, geology, groundwater table and topography, and combinations of these factors, can have a direct impact on the characteristics of faecal sludge. The extent of the impact will vary depending on the local conditions and the type of containment. For example, biological degradation of faecal sludge will depend on anaerobic conditions, temperature, total moisture, and inhibitory compounds (Bourgault, 2019; Bourgault *et al*., 2019; Byrne *et al.,* 2017; Van Eekert *et al*., 2019; Bakare, 2014). Moisture content is also dependent on the net inflow and outflow (or infiltration) of moisture, which depends on soil type, type of lining used, local topography, and groundwater level. Infiltration into containment from groundwater with a high water table can lead to the ‘floating’ of faecal sludge fractions in pit latrines and increase the water content of the sludge (Chirwa *et al*., 2017). Groundwater tables also fluctuate by season, which can result in different groundwater hydraulic conditions that can influence sludge characteristics throughout the year. Sandy soils are more permeable and allow for a higher exchange of water and gases, whereas clay-dominated soils are much less permeable and limit the exchange. Rainfall directly affects the groundwater table, and runoff from steep slopes can enter the containment through toilet openings or access ports. These factors are accounted for in the modelling approaches described in Chapter 6.

2.3.2.4 Variability of accumulated faecal sludge

The result of the demographic, environmental, and technical factors that influence characteristics of faecal sludge is a high level of heterogeneity that complicates characterisation. As shown in Figures 2.4 and 1.3, there is often no ‘standard range of variation’ for particular properties, and findings from one study cannot necessarily be used as a base of comparison to another. This is shown in Figure 2.4 with the level of variation of COD, ash content, moisture content, and calorific value in Durban, South Africa (Velkushanova *et al*., 2019; Zuma *et al*., 2015). Each data point represents the results of analysis from one faecal sludge sample, collected from the following containments: dry ventilated improved pit latrines (red); wet ventilated improved pit latrines (green); community ablution blocks (blue); urine-diverting dehydration toilets (UDDT, yellow); ventilated improved pit latrines in schools (purple); and unimproved pit latrines (turquoise). The mean value for each type of faecal sludge sample is presented as a dotted line in the respective colour. The level of variation is even higher within samples collected from the same type of onsite sanitation system than in comparison to other containments, which raises the question whether it is even possible to find statistical relations or predictors in this data. More details are presented in Chapter 5 on approaches and techniques for collecting and processing community to city-wide data sets of faecal sludge characteristics.

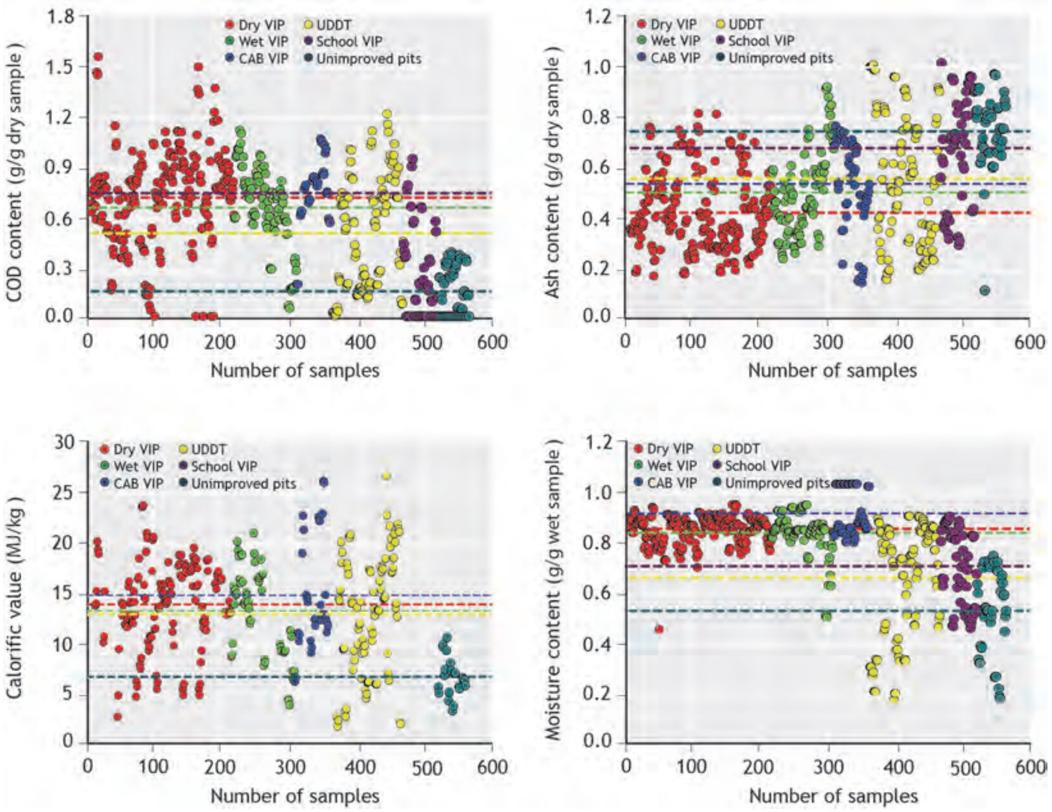

Figure 2.4 Variation of COD, ash content, moisture content, and calorific value properties of faecal sludge from different types of containment, collected in Durban, South Africa. Collectively, the total number of analysed replicates was 564, with a total of 188 samples all together for all the containment types, collected from different sections and depths within the containments. Each of these samples were analysed for properties such as moisture content, TS/VS, organic content such as COD, TKN, pH and electrical conductivity, thermal conductivity, calorific value, nutrient content, rheological properties and viscosity, and helminths (source: UKZN PRG[2]).

2.3.2.5 Developments and innovations in onsite containment

Some emerging innovative sanitation technologies combine the user interface ('front-end') with containment ('back-end'), to simultaneously contain and treat excreta onsite. For example, systems that are based on flush-type toilets can include membrane and other treatment processes to re-use the flushwater. One technology example is the nano-membrane toilet by Cranfield University (Figure 2.5, Parker, 2014). The user interface is a pedestal toilet with a waterless swiping flush mechanism, with waste-processing components housed within the pedestal. The solids are extracted by an auger, and then dried and combusted with only a small amount of ash remaining. The liquids are preheated and purified with a hydrophobic membrane, which is reusable. This system has been tested in communities in Durban, South Africa (Hennigs *et al*., 2019; Mercer *et al*., 2018), along with other innovative toilet systems, such as the Blue Diversion Autarky (Reynaert *et al*., 2020), and a household-scale onsite blackwater treatment system (Sahondo *et al*., 2020; Welling *et al*., 2020). If implemented at scale, these types of technologies could have a dramatic impact on the Q&Q of faecal sludge that accumulate, with the goal to eliminate accumulation as much as possible.

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[2] https://osf.io/uy7t2/

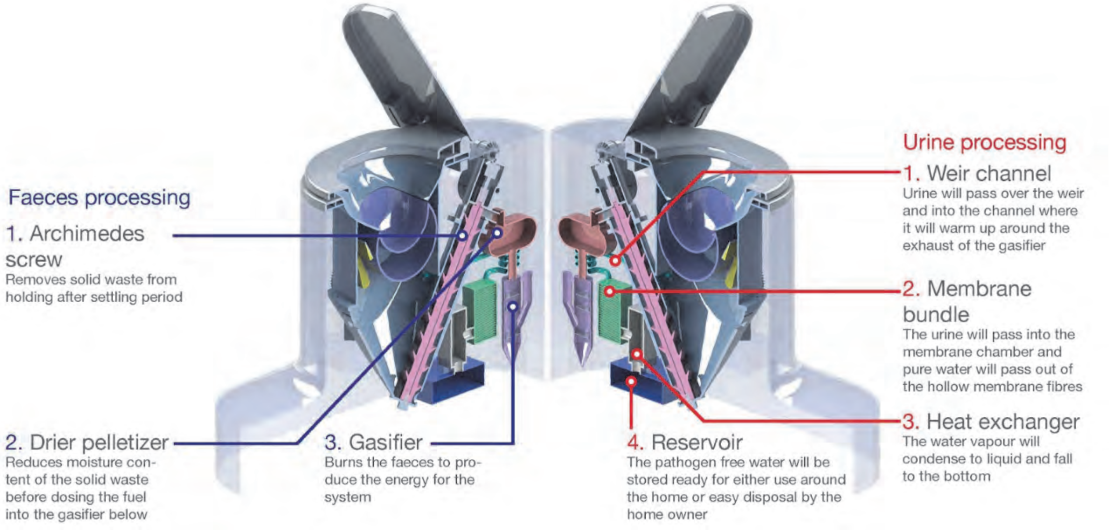

Figure 2.5 Nano Membrane toilet: an example of a waterless self-contained toilet (source: Cranfield University[3]).

Another example is the Solar Septic Tank - a technology aiming to enhance the degradation of solids and increase the quality of effluent by passive solar heating to 50-60 °C (Connelly *et al*., 2019, Figure 2.6). The heating promotes enhanced microbial degradation of both soluble compounds and retained solids, as well as partial pasteurisation of the liquid effluent prior to discharge. This technology has been installed and tested in Bangkok, Thailand and reported average removal efficiencies of total COD, soluble COD, and total biochemical oxygen demand (BOD) are between 90-99% over one year period (Koottatep *et al*., 2020).

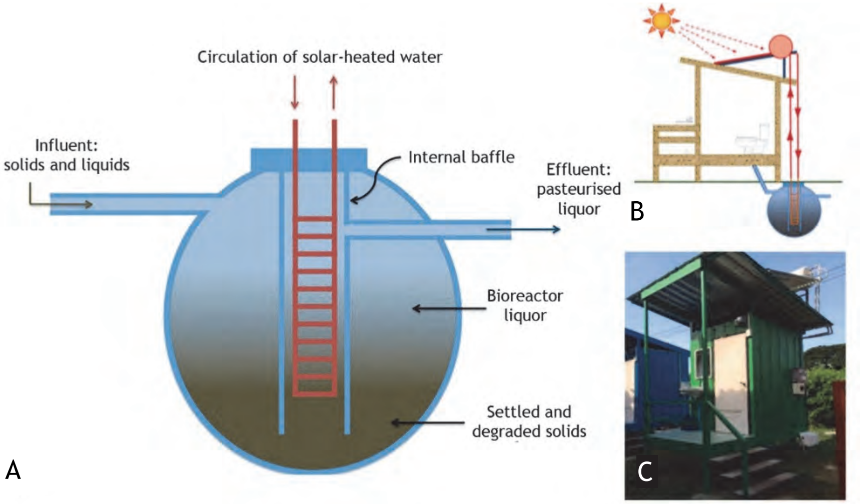

Figure 2.6 Principles of the Solar Septic Tank: (A) principles of solar heating applied to SST; (B) illustration of the buried septic tank and solar collection unit on the toilet roof; (C) installation of the SST in the field test site (source: AIT).

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[3] http://www.nanomembranetoilet.org

2.3.3 Emptying and transport

The emptying of faecal sludge from the onsite containment, followed by transportation to treatment, is the next step in the sanitation service chain.

2.3.3.1 Storage time or emptying frequency

The emptying frequency of sludge in onsite containments defines the sludge storage time, residence time, or 'age' of accumulated sludge. Depending on the type of containment, accessibility and usage patterns, sludge remains in the containment anywhere from days to weeks, to years or even decades (Taweesan *et al*., 2015; Strande *et al*., 2014; Tayler, 2018). With increased residence time in the containment, the sludge will be more stabilised, with rates of stabilisation depending on environmental factors. Rates of biodegradation impact nutrient cycling and stabilisation, which affect the dewaterability properties of faecal sludge and its suitability for treatment with different technologies. Fresher sludge is frequently observed to have poor dewatering performance due to the level of stabilisation (Ward *et al*., 2019, Chapter 4). Systems with a high number of users such as public toilets or commercial enterprises will also be more frequently emptied, meaning that the sludge will be 'fresher' and not as digested as older sludge. However, the faecal sludge accumulated in public toilets does not fit into one type of faecal sludge and will vary in characteristics depending on the type of containment technology, local context, and other environmental factors (Appiah-Effah *et al*., 2014; Heinss *et al*., 1998; Strauss *et al*., 1997; Strande *et al*., 2018). An example of public toilets are community ablution blocks (CAB) in Durban, South Africa (Figure 2.7). The CAB is a system that uses old shipping containers as a superstructure equipped with toilets, wash basins and showers (Starkl *et al*., 2010). Since high volumes of greywater from bathing and laundry are inputs to the containment, the faecal sludge is classified as liquid with low TS.

Figure 2.7 Community ablution blocks in Durban, South Africa (source eThekwini Municipality, photo: UKZN PRG).

2.3.3.2 Manual or mechanical emptying

The method of emptying can influence faecal sludge characteristics, and *vice versa* the characteristics of faecal sludge in the containment can dictate possible methods of emptying (Zziwa *et al*., 2016; Balasubramanya *et al*., 2016; Chipeta *et al*., 2017). If faecal sludge is too thick it is not pumpable and will require manual emptying (e.g. measured as moisture content, viscosity, or rheological properties) (Bosch and Schertenleib, 1985; Radford and Fenner, 2013). Excessive amounts of solid waste can also prevent pumping due to blockage or breakage of the sludge emptying equipment (Ahmed *et al*., 2018). In addition, if the site is not accessible by larger vehicles (*e.g.* trucks), it will also require manual emptying. Mechanical collection with vacuum trucks is also not possible if the solid content of faecal sludge is too high (Mikhael *et al*., 2014). Due to these limitations on which type of emptying technologies can be used, faecal sludge that is collected mechanically can have different properties to faecal sludge that is collected manually. In adition, faecal sludge demonstrates shear thinning characteristics (meaning that it can become more liquid with an increasing shear rate), which can result in changes in viscosity of faecal sludge after mechanical collection (Septien *et al*., 2018a). Another example is the addition of water into containments before emptying to dilute the sludge and make it easier to remove. This results in modified characteristics of faecal sludge, such as higher moisture content and reduced viscosity. Based on factors such as thickness, depth of containment, and affordability of service, the sludge is also not always entirely removed (Nakagiri *et al*., 2015; Semiyaga *et al*., 2015; Chiposa *et al.,* 2017). For example, in Durban, it was observed that sludge in the bottom of pit latrines was the oldest and most stabilised, compared to the upper layers of the pit latrine containment (Buckley *et al*., 2008; Bakare *et al*., 2012).

2.3.3.3 Transportation

Transportation can be done manually with carts, or motorised with trucks (Mikhael *et al*., 2014). The effect of transportation on faecal sludge characteristics is not clear, but samples taken from transport trucks have different concentrations of TS and COD than those taken directly from containment (see Case Study 3.3). Solids also separate out in the bottom of vacuum trucks during transport. Another possibility for increasing the efficiency of transport is transfer stations. Possibilities include a tank installed for delivery of sludge by manual emptiers who cannot transport sludge long distances, which could then be transferred to treatment by trucks, and/or as a dewatering step with supernatant going to a sewer and dewatered sludge being transported to treatment (Strande, 2017). There are not yet many examples of successful implementations. However, one that is currently being field-tested in Nairobi, Kenya appears promising (Junglen *et al*., 2020).

2.3.3.4 Innovations in faecal sludge emptying and transportation

Emptying of faecal sludge, particularly mechanical emptying, is challenging due to inaccessibility, high TS and solid waste content and the high heterogeneity of faecal sludge characteristics, which makes it difficult to have sludge emptying technologies that are uniform for all types of faecal sludge and onsite sanitation technologies.

A number of innovative technologies for faecal sludge emptying are trying to address these challenges, in order to empty sludge with a higher TS and level of stabilisation from pit latrines. For example, the Flexcrevator is a technology developed by North Carolina State University (Sisco *et al*., 2017; Rogers *et al*., 2014; Portiolli, 2019; Figure 2.8). It consists of a vacuum tank, external extruder and a flexible screw, operating simultaneously to extract the faecal sludge while pushing away the solid waste materials. In this way the sludge is emptied while the solid wastes remain in the containment. The Flexcrevator is relatively small in size to enable access to containments that normally cannot be reached by vacuum tankers.

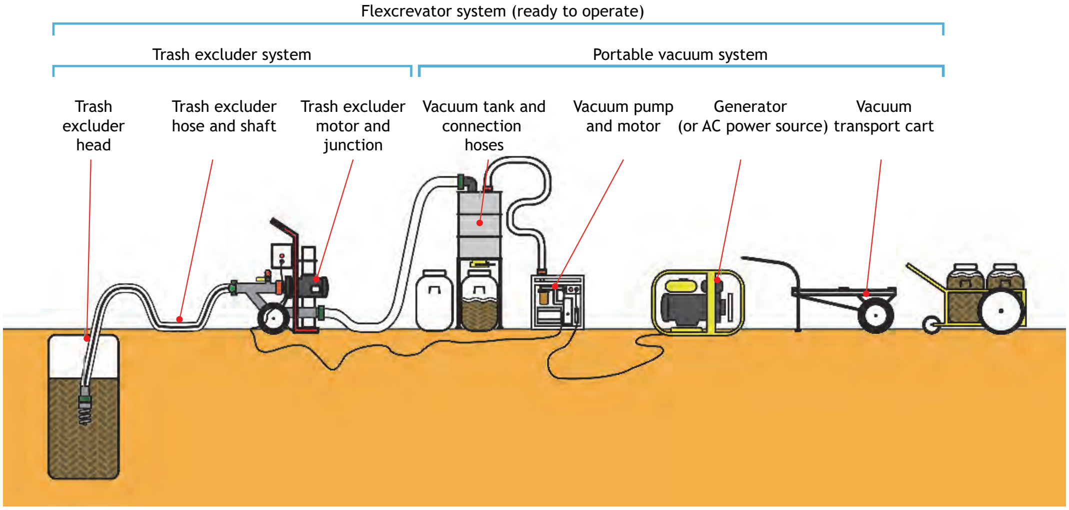

Figure 2.8 Innovative technology for faecal sludge emptying - the Flexcrevator (source: North Caroline State University[4]).

2.3.4 Treatment and end use

2.3.4.1 Faecal sludge treatment plants

There are several technology options for the treatment of faecal sludge. Faecal sludge treatment plants that are currently in operation are commonly decentralised or semi-centralised, with the faecal sludge being delivered by trucks following collection. The four main treatment objectives are stabilisation, nutrient management, pathogen inactivation, and dewatering/drying (Niwagaba *et al*., 2014; Strande, 2017). The characteristics of faecal sludge during treatment will be significantly different, and depend on the treatment objectives and location in the treatment chain (see example 3.5.3). A typical treatment chain includes preliminary separation, settling-thickening tanks, drying beds, with the leachate going to treatment in stabilisation ponds and/or co-treatment with wastewater, and resource recovery or disposal of the dewatered sludge (Klinger *et al*., 2019). For concerns related specifically to characteristics of faecal sludge regarding treatment potential, the reader is referred to the following freely available reference books: Tayler (2018); Strande *et al.* (2014); Englund and Strande (2019); Robbins and Legon (2014); Polprasert and Koottatep (2017); and Narayana (2020).

Preliminary separation processes usually include screening to remove large objects and waste from the sludge. Solids that are removed in settling-thickening tanks varies depending on the specific characteristics of faecal sludge (Dodane and Bassan, 2014; Gold *et al*., 2018; Ward *et al*., 2019). This is an important distinction, as different types of sludge have widely varying characteristics and are not comparable. How properties such as different redox conditions, level of stabilisation, biomass, nutrients, particle size, undigested plant fibres, salts and ions, and extracellular polymeric substances (EPS) affect dewaterability is not yet fully understood (Bourgault *et al*. 2019; Ward *et al*., 2019). An example of ranges of dewaterability is provided in Figure 2.9. The turbidity of the supernatant of faecal sludge samples following centrifugation in the laboratory appeared quite different. In addition, the more stabilised sludge dewatered more quickly, and the less stabilised sludge had more clogging of filters, possibly due to higher concentrations of EPS (Ward *et al*., 2019). As scientific knowledge is advanced, the use of conditioners will be possible to reduce total suspended solids (TSS) in the effluent of settling tanks, and reduce drying time on drying beds (Gold *et al*., 2016; Ward *et al*., 2021).

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[4] https://www.globalinnovationexchange.org/innovation/flexcrevator-a-pit-emptying-device

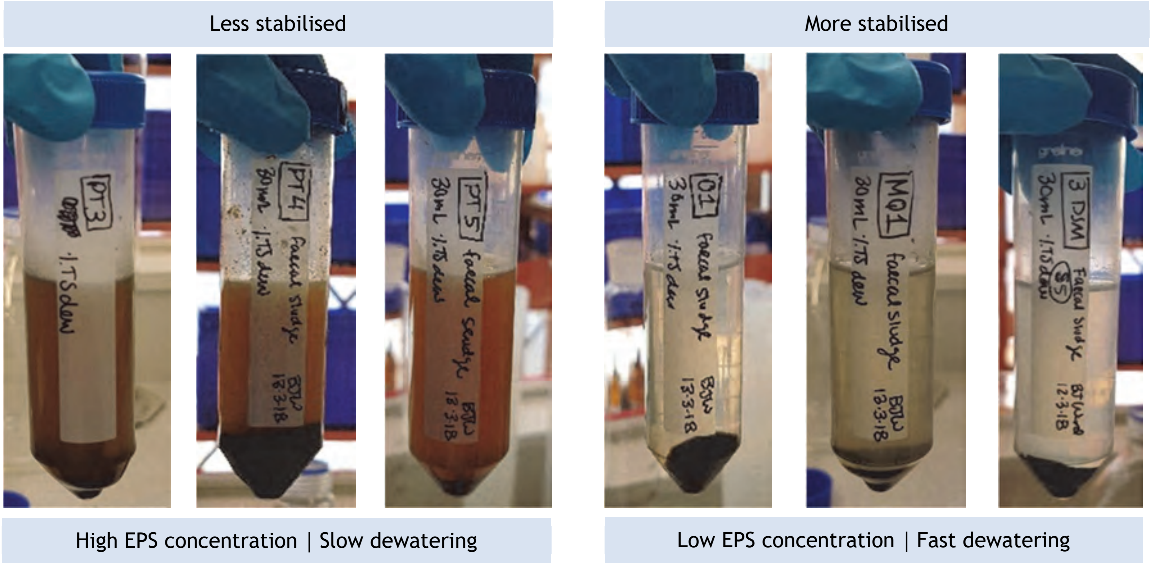


Figure 2.9 Comparison of supernatant turbidity following centrifugation of faecal sludge samples in Dakar, Senegal (source: Ward *et al.*, 2019).

The TSS that separate out in settling-thickening tanks are loaded batch-wise onto unplanted drying beds, or continuously onto planted drying beds (Englund and Strande, 2019). The leachate that percolates through the drying beds requires further treatment, as it is high in salts, organic content, nutrients, and pathogens, with loadings similar to influent concentrations of wastewater treatment plants (Kengne *et al.*, 2014; Seck *et al.*, 2015; Sonko *et al.*, 2014; Thomas *et al.*, 2019). The leachate is usually treated together with the supernatant from the settling-thickening tanks. Following successful dewatering, sludge on drying beds is semi-solid to solid, and can be removed by hand or with a shovel, as shown in Figure 2.10. Other established treatment technologies include co-composting with organic solid waste (Nikiema *et al.*, 2014).

Figure 2.10 Removal of semi-solid to solid dewatered sludge from drying beds at Camberene treatment plant in Dakar, Senegal (photo: Eawag).

2.3.4.2 End use or disposal

As shown in Table 2.1, there are many possibilities for resource recovery from faecal sludge, and research is actively taking place on improving recovery as energy (Andriessen *et al.*, 2019; Krueger *et al.*, 2020; Onabanjo *et al.*, 2016;), nutrients and organic matter (Nikiema *et al.*, 2014; Orner and Mihelcic, 2018; Hashemi and Han, 2019; Roy *et al.*, 2019; Simha *et al.*, 2017), and animal fodder as black soldier fly and plants (Lalander *et al.*, 2013 and Gueye *et al.*, 2016). Characteristics of concern will be dependent on the final end use; for example, for use as a fuel, the water content and calorific value are important to evaluate (Murray Muspratt *et al.*, 2014), whereas for use as a soil amendment, pathogens and heavy metals are important. Further examples of characteristics for the consideration of resource recovery are covered in Section 2.4.

Table 2.1 Potential faecal sludge treatment products and type of resource recovery (source: Schoebitz *et al.*, 2016).

Resource	Treatment product	Product type
Energy	Solid fuel	Pellets, briquettes, powder
Energy	Liquid fuel	Biogas
Energy	Electricity	Conversion of biogas or gasification of solid fuel
Food	Protein	Black soldiers flies, fish meal
Food	Animal fodder	Plants from drying beds, dried aquaculture plants
Food	Fish	Fish grown on effluent from faecal sludge treatment
Material	Building materials	Additive to bricks, road construction materials
Nutrients	Soil conditioner	Compost, pellets, digestate, black soldier fly residual
Nutrients	Fertiliser	Pellets, powder
Nutrients	Soil conditioner	Untreated sludge, dewatered sludge from drying beds
Water, nutrients	Reclaimed water	Effluent from faecal sludge treatment

2.3.4.3 Innovations in treatment and end use

Several innovative and emerging faecal sludge processing technologies have been developed to treat faecal sludge at scale. Some of them are based on unconventional faecal sludge processes such as hydrothermal oxidation, pyrolysis, gasification, combustion thermal drying, infrared irradiation, microwave irradiation, black soldier fly larvae and vermicomposting, to reduce the sludge volume and pollutants, inactivate pathogens and convert the sludge components into valuable resources (Hiolski, 2019; Mawioo *et al.*, 2017; Fakkaew *et al.*, 2018; Septien *et al.*, 2018b; Yadav *et al.*, 2012). For example, the omniprocessor is a faecal sludge treatment technology using combustion that treats human waste and produces drinking-water quality water, electricity and ash. In the case of full water reclamation, it is important to evaluate characteristics for the protection of public health, including pathogens, heavy metals, and pharmaceuticals. The pilot of this technology is installed in Dakar, Senegal (Figure 2.11). Other examples of innovations are included in chapters 4, 5 and 6.

Figure 2.11 The omniprocessor faecal sludge treatment system in operation in Dakar, Senegal (photos: UKZN PRG and Sedron Technologies).

2.3.4.4 Container-based sanitation (CBS)

The business model and technology implementations for container-based sanitation (CBS) have rapidly progressed over the last decade, and are now classified as a type of improved sanitation facility by the Joint Monitoring Programme (Figure 2.12, Russel *et al.*, 2020; World Bank, 2019, Brdjanovic *et al.,* 2015).

Faecal sludge from CBS tends to have a much higher TS content than other faecal sludge, as most CBS toilets do not collect flushwater and grey water, and many are also urine-diverting with a dry desiccant as cover material. For example, the average TS content observed in Sanivation toilets, a Kenyan-based CBS service provider, is 60% (personal communication, Woods E.). Other differences include much less solid waste mixed in with the faecal sludge, and a higher C/N ratio due to carbon-rich cover material (*e.g.* ash, saw dust, bagasse). Faecal sludge is transported manually with trolleys, pickups, or tuk-tuks in containers to treatment plants (Figure 2.12). Therefore, it tends to arrive at the faecal sludge treatment plants in relatively small batches throughout the day.

If off-grid, self-contained solutions are successfully scaled up, it could significantly impact the faecal sludge management service chain. The considerations for characterisation are specific to the technology and operation, and the design of such systems will also potentially be context-specific based on regional characteristics, as described in Section 2.1.1.

2.3.4.5 Summary of technologies along the sanitation service chain

A wide range of technologies that correspond to management of faecal sludge at each step in the sanitation service chain are summarised in Table 2.2. There are varying levels of knowledge as to the effects of different technologies on the characteristics of faecal sludge. As also presented in chapters 1 and 4, based on the current operational experience and practical knowledge, they can be grouped into established, transferring, and innovative technologies (WHO, 2018).

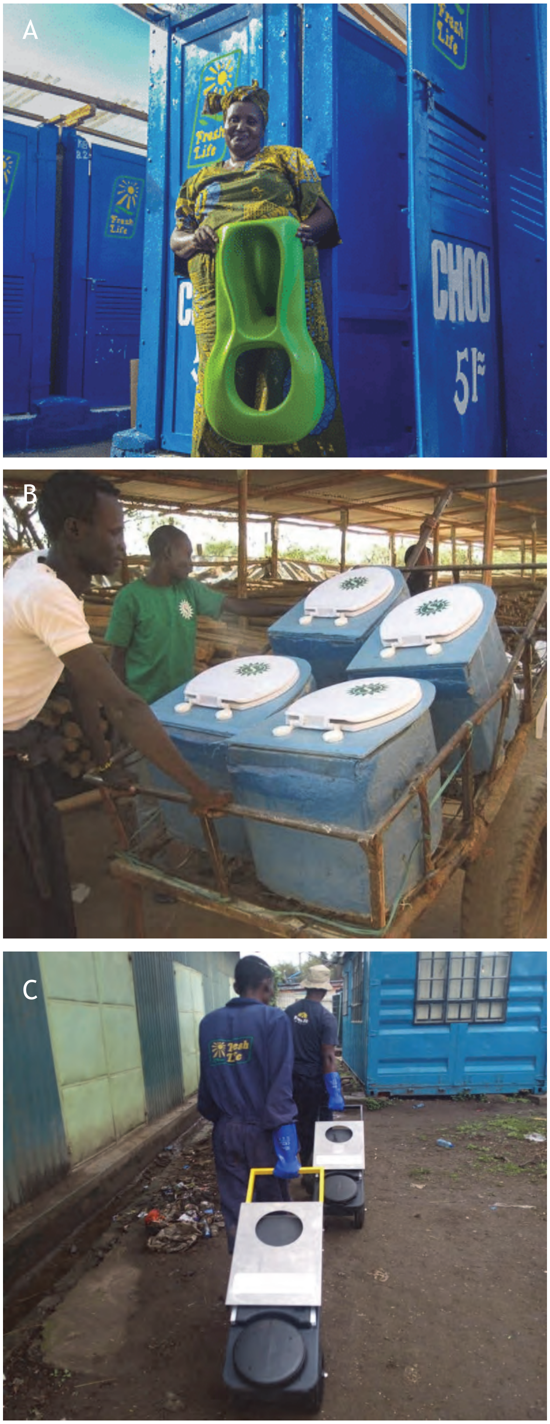


Figure 2.12 Examples for CBS from Sanergy (A) and Sanivation (B), both based in Kenya, and (C) eSOS Smart Toilet field-testing in Nairobi (photos: World Bank and IHE Delft).

Table 2.2 (Part 1 of 2) Examples of established, transferring, innovative and container-based sanitation technologies along the sanitation service chain.

Technology application	Toilet (user interface)	Collection & storage (containment)	Emptying & transport (conveyance)	Treatment	End use and/or disposal
Established and transferring	*Dry* • Open hole pedestal • Open hole squatting • Urine-diversion dry • Urinal *Water-based* • Pour flush toilet • Low flush toilet • Urine-diversion flush toilet • Cistern flush	*Waterless* • Ventilated improved pit latrine (VIP) • Composting toilet • Urine storage tank • Urine diversion and dehydration vault *Water-based* • Pit latrine • Tank • Septic tank • Leach pit • Soak pit • Aqua privy	*Manual* • Shovel • Bucket • Cart for transportation • Sludge gulper • Diaphragm pump • Nibbler • MAPET • Hook and claw *Mechanised* • Vacuum tanker • Vacutug • Micravac • Motorised diaphragm • Trash pump • Gobber • Motorised screw auger	*Established* • Settling-thickening tank • Stabilisation pond • Unplanted drying bed • Planted drying bed • Co-composting *Transferring* • Mechanical dewatering • Conditioners • Alkaline treatment • Lime stabilisation • Incineration • Anaerobic digestion • Pelletising • Thermal drying	*End use products* • Biogas • Compost • Treated leachate • Ash • Fodder/animal feed • Effluent *Disposal* • Landfill • Burial
Emerging and innovative	*Front-end component* • EOOS • Urine-diversion toilets • Waterless flush toilets • Nano Membrane Toilet • eSOS Smart Toilet • MEDiLOO	*Back-end treatment* • Gasification • Biogas reactor • Anaerobic baffled reactor • Peepoo • Compost filter • Black soldier fly larvae • Hydrothermal carbonisation • Microwave treatment • Microbial fuel cells • Nanomembrane • Membrane bioreactor • Bioelectrical processing • Dry combustion • Drying			*End use products* • Hydrochar • Biochar • Biogas • Biodisel • Liquid fertiliser • Protein • Animal feed • Oil • Electricity • Heat • Purified water

Table 2.2 (Part 2 of 2) Examples of established, transferring, innovative and container-based sanitation technologies along the sanitation service chain.

Technology application	Toilet (user interface)	Collection & storage (containment)	Emptying & transport (conveyance)	Treatment	End use and/or disposal
Emerging and innovative			*Emptying of faecal sludge from established onsite containments* • Modified sludge gulper • Extraction auger • Flexcevator	*Treatment at scale of faecal sludge from established onsite containments* • Omni Processor • Supercritical water oxidation • Black soldier fly larvae • Vermicomposting • Infrared radiation (LaDePa) • Urine treatment (struvite reactor) • Hydrothermal carbonisation • Combustion • Pyrolysis • Microwave radiation (Shit Killer, Tehno Sanitizer)	*End use products* • Hydrochar • Biochar • Biogas • Biodisel • Liquid fertiliser • Protein • Animal feed • Oil • Electricity • Heat • Purified water
Emerging and innovative Container-based sanitation (CBS)	*CBS toilets* • Sealed container, often urine-diverting • Waterless • Usually portable	*Emptying* • Regular collection via service provider • Replace full containers with empty clean containers	*Transport* • Push carts • Collection depot • Large transport vehicle • Full containers are sealed and transported to treatment or disposal site	*Treatment* • Various treatment processes from pathogen reduction to full resource recovery (*e.g.* thermophilic composting, urine nitrification) • Containers are emptied, cleaned and disinfected before reuse	*End use and products* • Compost • Biogas • Biomass fuel • Animal feed • Phosphorus and nitrogen from urine

2.4 PROPERTIES OF FAECAL SLUDGE AND SELECTING METHODS OF CHARACTERISATION

The characterisation and understanding of the properties of faecal sludge as a material is crucial for the provision of integrated faecal sludge planning, management and treatment solutions through the entire sanitation service chain. The first step in the characterisation process of faecal sludge is to determine the purpose and the objectives of the characterisation (Figure 2.13). The purpose is the reason, for example, selecting and designing a faecal sludge treatment technology, with the objective to maximise valorisation potential. Common reasons for characterising faecal sludge could involve setting up a monitoring program at a treatment plant, defining a research question, designing and developing new processes or technologies, or collecting data to design an integrated faecal sludge management plan. Specific examples of characterisation objectives include:

- Understanding biochemical processes of degradation and nutrient cycling
- Evaluating faecal sludge stabilisation with location and time in onsite containment technologies
- Planning of emptying services for a community
- Selecting the best technology for emptying of sludge from onsite containments
- Designing an innovative toilet and containment solution
- Designing a new technology for emptying or treatment
- Designing a new faecal sludge treatment plant
- Determining loadings for the operation of a treatment plant
- Evaluating operational parameters during the start-up phase of a faecal sludge treatment plant
- Monitoring a treatment plant for overall treatment efficiency and pathogen removal
- Evaluating potential for resource recovery
- Assessing compliance with requirements for end use
- Quantifying resource recovery value (*e.g.* energy, food, nutrients, water).

Once the purpose and the objectives are defined, then the type of properties to measure in the characterisation process can be determined. For example, if the purpose is the design of a thermal treatment technology for resource recovery as a fuel, important parameters to measure include moisture content, TS, VS, thermal conductivity, heat diffusivity and calorific value. In this particular case, the measurement of COD will be of secondary importance. On the other hand, if the purpose is to design an anaerobic digester, the total bio-degradable organic matter will be important to determine, and can be evaluated with analytical methods such as BOD, COD, and volatile solids. It would also be important to measure moisture content, TS, TSS, NH_3, and other macro- and micro-nutrients. In this case, there is no need to measure thermal conductivity and calorific value of the faecal sludge, because these properties are not directly related to the design parameters of anaerobic digestion.

In this book, faecal sludge properties are grouped into three main groups: (*i*) chemical and physico-chemical, (*ii*) physical, and (*iii*) biological, details of which are provided in Section 2.4.1.

The next step in the characterisation process is the selection of suitable methods for analysis, based on factors such as type of faecal sludge (based on TS), level of accuracy of the required results, costs of analysis, and laboratory capacity (see Section 2.4.2). The selection of methods is an essential part of the planning process before undertaking the sample collection, as it involves considerations such as budget and time restrictions, and the availability of instruments and trained personnel to undertake the analysis. Figure 2.14 provides an overview of this decision-making process.

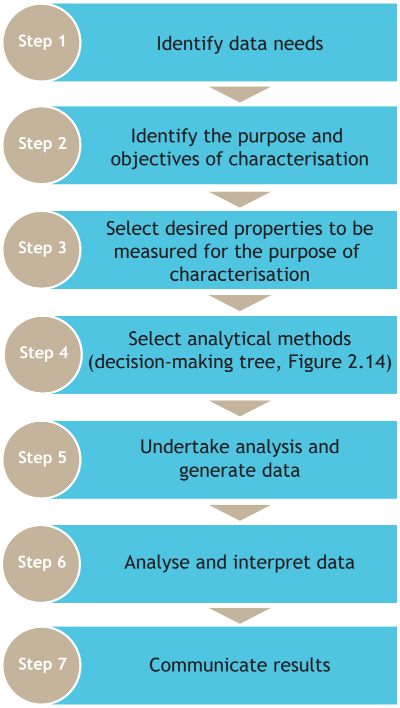


Figure 2.13 Steps in the faecal sludge characterisation process. Further information on how to select analytical methods (Step 4) is provided in Section 2.4.2. Further information on the integrated approach for data collection, analysis and interpretation within the entire book is provided in Chapter 1, and further information on integrating characterisation into a sampling plan is included in Chapter 3.

After selecting suitable methods for the purpose of characterisation, the next steps are undertaking the analysis, followed by data analysis and interpretation to fulfil the purpose of characterisation. The laboratory methods for the analysis of faecal sludge presented in this book are summarised in Section 8.4, Table 8.3, with cross references to where they are located in Chapter 8. Many methods have been adapted from methods for water and wastewater, in addition to soil and food science. The methods presented here are the first step towards standardisation of methods and procedures for faecal sludge analysis. As the need for additional methods arises, they will also need to be developed or adapted from standard methods. One of the challenges of adapting methods is the high heterogeneity of faecal sludge characteristics, which requires special care. Examples are steps for sample homogenisation, filter size due to clogging, and sample volume for representativeness. For more information on developing methods, refer to the tips for adapting methods specific to faecal sludge included in Chapter 8, and standard method 1040 on development and evaluation in Standard Methods for the Examination of Water and Wastewater (Rice *et al*., 2017). As more methods become established, they will be included in future editions of this book. It is important to keep in mind, even when following established methods for faecal sludge, that they need to be adapted for the local and institutional context. For example, in Lusaka the temperature had to be increased near the end of TS drying time due to swelling of the faecal sludge (Ward *et al*., 2021). For information on sampling handling and preparation, refer to Chapter 3 and Chapter 8.

2.4.1 Faecal sludge properties

Following is a brief discussion of the chemical and physico-chemical, physical, and biological, properties of faecal sludge and their relevance to the management of faecal sludge.

2.4.1.1 Chemical and physico-chemical properties

Chemical properties refer to properties of materials that change as a result of chemical reactions, for example oxidation state, and whether they are flammable, corrosive, radioactive, or an acid or base. Physico-chemical properties are dependent on both physical (see Section 2.4.1.2) and chemical processes, and are determined by the interactions of components within faecal sludge.

Solids and moisture content

Fractions of TS and moisture content are important for determining appropriate emptying methods for onsite containment technologies, loadings of technologies such as drying beds and settling-thickening tanks, and to evaluate dewatering and drying performance. As defined in Section 2.2, and further explained in Chapter 8, the four defined types of faecal sludge by TS are also used to determine analytical methods, and sample preparation and handling (liquid TS <5%, slurry TS 5-15%, semi-solid TS 15-25%, and solid TS>25%).

The moisture content of faecal sludge is highly variable, resulting in uncertainties when expressing different properties based on the total volume or mass. For more liquid samples, the volumetric method is used because it provides more precision, with concentrations reported as gTS/L total sample volume. For semi-solid or solid samples, the gravimetric method is more precise and concentrations are reported as gTS/g total wet mass of the sample. The density can be used to convert between volumetric and gravimetric for comparison to values in the literature. Total solids can be divided into categories based on organic content (volatile or fixed), and based on physical properties (suspended and dissolved). Total solids can be fractionated into total fixed solids and volatile solids by ignition at 550 °C. Total fixed solids (ash) are the material left behind after ignition, and are the minerals that do not biodegrade over time (*e.g.* inorganic inputs and soil in pit latrine samples). Volatile solids are volatised during ignition at 550 °C and are an indicator of the biodegradability of samples. Care has to be taken not to directly transfer empirical relations from wastewater, as the VS/TS ratio of faecal sludge is heavily influenced by the wide range of inorganic substances in samples. Dissolved and suspended solids are defined by their physical properties. Total solids can be fractionated into total dissolved solids (TDS) and total suspended solids (TSS) through filtration. TDS are defined as being the solids contained in the filtrate that passes through a filter with a pore size of 2.0 µm or less, whereas TSS are not as well defined. Suspended solids are defined as those that do not pass through a filter, but the pore size of filter paper ranges from 0.45 to 2.0 µm due to the clogging of filters with thicker samples. This is why it is especially important to document with clear methods exactly how analysis was carried out.

The moisture content will directly and indirectly affect the biodegradability and viscosity of faecal sludge, the solid-liquid separation and dewaterability potential, pumpability, viscosity, shear thinning, mixing, and drying. Steps for measuring and calculating moisture content of different fractions of solids (TS, VS, TSS) are provided in Chapter 8.

Organic content

Organic matter is important for evaluating the level of stabilisation of faecal sludge, biodegradation potential for biological treatment, and impact on receiving environments. Total organic carbon (TOC) and COD are measurements of the total organic fraction of carbon. COD is measured as the amount of an oxidant (*e.g.* dichromate in acid solution) that reacts with the sample, chemically oxidising it. The results are reported in oxygen equivalents. COD will always be greater than the biodegradable fraction of organic matter, as the strong chemical oxidant can oxidise more organic carbon bonds than biological reactions. The BOD_5 assay is an empirical test to quantify the fraction of organic content that is biodegradable.

Since faecal sludge is stored under predominantly anaerobic conditions, more experimental work needs to be conducted on the best ways to measure stabilisation and potential for biodegradation during treatment. This is important, as the level of stabilisation is related to the dewaterability of faecal sludge, and the potential for biological treatment, as discussed further in Chapter 4. Aggregate methods for concentrations of organic matter are provided in Chapter 8, but not for individual compounds (*e.g.* trace organic contaminants).

Nutrient content

Nutrients in faecal sludge are present in organic or inorganic forms. Nutrients are important to monitor for NH_3 inhibition, adequate nutrients for biological processes, fate in the environment, and potential for valorisation in agriculture as compost or fertiliser. Total Kjeldahl Nitrogen (TKN) is a metric of the sum of organic nitrogen and NH_3. To quantify organic nitrogen, the NH_3 concentration can be measured and subtracted from TKN. Other forms of inorganic nitrogen are nitrate (NO_3^-) and nitrite (NO_2^-). The different forms of nitrogen provide information on the redox potential (*e.g.* aerobic, anaerobic, anoxic) of faecal sludge, and level of stabilisation in biological processes such as compost (Nikiema and Cofie, 2014). Similarly, total phosphorus includes organic and inorganic forms. Ortho-phosphate (PO_4^{3-}) is the inorganic form, which is soluble and bioavailable.

pH, conductivity alkalinity and corrosion

pH is important to measure as it can influence reaction rates, chemical speciation, and biological processes, and also because it can be an indicator of the source of the faecal sludge (*e.g.* industrial contamination). Sample preparation and how the pH is measured is an important factor, as the method can change the pH of the sample. Conductivity is a metric of ions in a solution. Ion concentration is important as high salt concentrations can inhibit biological processes such as in stabilisation ponds. Alkalinity represents the acid-neutralising capacity of water, and is commonly referred to as 'soft' or 'hard' water. Alkalinity is important in many biological processes, such as nitrification, which consumes alkalinity and lowers pH (7.07 $gCaCO_3/gNH_4\text{-}N$, plus additional alkalinity to maintain pH) (Tchobanoglous *et al*., 2014). Corrosion potential (EC, pH, Cl^-, $CaCO_3$, H_2S) is important for tanks and pipes, and can lead to failure.

Metals

Chemical elements are important to quantify, as varying concentrations of metallic elements (*e.g.* macro and micro-nutrients) are necessary for treatment performance (*e.g.* microbial growth) and plant and animal growth (*e.g.* iron, chromium, copper, zinc, and cobalt), but can also be toxic depending on their concentrations. Guidelines for heavy metal concentrations for land application of sludge are summarised in Hanay *et al*. (2008), McGrath *et al.* (1994) and ISO 31800 (2020).

2.4.1.2 Physical properties

Physical properties are characteristics that do not change the chemical composition of a material such as faecal sludge. Examples of physical properties are density, particle size, turbidity, colour, odour, and thermal conductivity.

Settleability and dewaterability

Metrics of settleability and dewaterability are important for the operation of treatment plants, as dewatering is one of the most important steps in the treatment process. Metrics can include general settleability in a settling-thickening tank (Imhoff cone), dewaterability (centrifuge), and time for dewatering on drying beds or geotextiles (*e.g.* capillary suction time (CST)). Settleability and dewaterability can vary significantly depending on sludge characteristics, such as solids concentration and level of stabilisation.

Mechanical properties

Mechanical properties of faecal sludge are important for the design and sizing of emptying technologies (*i.e.* manual and mechanical), collection and transport options, and for the design of onsite sanitation systems and offsite treatment facilities. Measurements such as density, particle size, and rheological properties provide information on the 'pumpability' of materials, or the 'stiffness' versus the ability to 'flow'. The overall tendency of faecal sludge is that it tends to 'flow' - a phenomenon known as 'shear thinning', where the increasing shear rate is expected to ease emptying processes from onsite containments (Septien *et al*., 2018a).

Thermal properties

Evaluation of thermal properties such as thermal conductivity and diffusivity, specific heat, and calorific value are important for resource recovery implementations with treatment end products, such as combustion as a solid fuel or biofuel. The calorific value of a material is the quantity of heat produced by combustion. Thermal conductivity is the ability of a material to conduct heat and is important for assessment and understanding of faecal sludge end use processes such as combustion and composting. Heat capacity is the quantity of heat energy required to change the temperature of an object by a given amount.

2.4.1.3 Biological properties

Biological examinations of samples are important along the entire service chain. The above chemical and physicochemical, and physical properties create a habitat for many organisms. Some are involved in nutrient and organic cycles, some are pathogens, and others can be associated with environmental impacts and resource recovery. Biological activities related to production and consumption of organic matter, or respiration, are included under the physico-chemical section. Further types of analytical methods for biological examinations include identifying pathogens (*e.g.* virus, bacteria, protozoa, helminths), metrics of toxicity (*e.g.* use of bioassays), enumeration (*e.g.* plate counts, flow cytometry, MPN), and types and functions of organisms (*e.g.* DNA/RNA analysis). The methods presented in Chapter 8 focus on pathogens.

Pathogens

Monitoring of pathogens is essential for the protection of public health, to protect workers handling sludge, to verify treatment efficiency prior to discharge, and for resource recovery. A risk-based approach can be taken to determine the adequate level of pathogen removal depending on the intended end use (WHO, 2015; WHO, 2018). Chapter 8 covers helminth eggs, as they are one of the most resistant pathogens to remove during treatment, and *E.coli*, as it is a type of faecal coliform that is used as an indicator of faecal contamination or of other organisms that can be present.

2.4.2 Selection of appropriate methods for characterisation

After defining the purpose, objectives and the desired properties to determine the characterisation process, the next step is to select appropriate methods for analysis. There are no strict guidelines to adhere to, but general considerations are the TS content, required level of accuracy, available resources, and laboratory capacity, as summarised in Figure 2.14 and explained in the following section. The sampling plan prior to analysis is discussed in Chapter 3.

Type of faecal sludge samples defined by total solids content

The type of faecal sludge samples defined by TS (liquid TS <5%, slurry TS 5-15%, semi-solid TS 15-25%, or solid TS >25%) should always be taken into consideration before designing a plan for characterisation. Some of the methods for sample preparation, chemical analysis, and solids fractionation in Chapter 8 are different for more liquid sludge or for semi-solid or solid sludge. For example, faecal sludge from dry sanitation facilities can require higher dilution during the sample preparation, compared to FS samples coming from wet sanitation facilities. In practice, the easiest way to determine the type of faecal sludge is to conduct a preliminary TS analysis of the faecal sludge that is going to be characterised.

Level of accuracy

The level of accuracy is defined by the purpose of characterisation, the laboratory equipment used for a particular analysis, and the level of competency required to undertake this analysis. For a particular analysis, the level of accuracy could be of high importance. For example, molecular tests to establish pathogenic or other groups of microbial populations require a high level of accuracy and sample preparation using specialised techniques and methods. In other cases, the level of accuracy is not as significant and the priority could be almost immediate data to establish the presence of pathogens, nutrients or TS. In this case, simple test kits can be used, either simple field or laboratory-based techniques. In reality, it is not always possible to obtain the desired level of accuracy as this will be related to the available budget resources. It should also be noted that some parameters have higher degrees of built-in inaccuracy due to the imperfection of analytical and measuring equipment or preparation and handling procedures of a sample.

Cost of analysis

The cost of the analysis is determined by the type of analysis and equipment. Costs of equipment and required laboratory consumables vary enormously, which also needs to be taken into account. Determining the number of samples is discussed in chapters 3 and 5. For example, for a particular project on faecal sludge characterisation, the number of samples to provide statistically significant results could be 300, but in reality, the available budget might only allow for analysis of 100 or even 50 samples. In this case, focus should be placed on the selection of the most representative number of samples from specific areas, together with rigorous quality assurance and control measures (QA/QC). The cost of analysis is one of the main parameters that will determine the scope and duration of a sampling campaign. For more detailed information on data handling, the reader is referred to Von Sperling *et al.* (2020).

Laboratory capacity

The laboratory capacity is defined by the skill level required for a particular analysis, the availability of the desired equipment, and the number of analyses that the laboratory is able to carry out in a certain period. This includes special technical staff in the laboratory to undertake the desired analysis, or whether they could be performed by an employee, researcher, field worker, or student. For example, the TS content method using an oven at 105 °C is a relatively simple method that does not require extensive training, while determining the calorific value with a bomb calorimeter requires a higher level of training to operate the more sophisticated equipment.

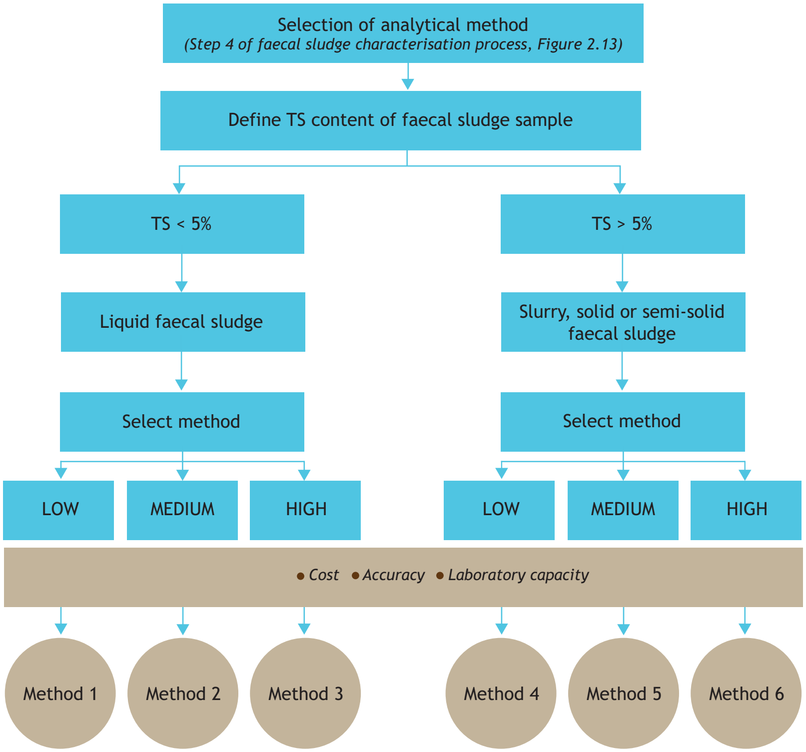


Figure 2.14 An example of a decision-making tree for the selection of a method of analysis depending on the purpose of characterisation. Step 4 refers to Figure 2.13, Steps in the faecal sludge characterisation process. Note: This example is specific to methods that differ for less than or are greater than 5% TS.

In Chapter 8, different methods based on the required level of accuracy (low, medium, or high) are provided (Figure 2.14, Section 8.4). This is based on the assumption that a high level of accuracy will be the most expensive option and will require more specialised laboratory equipment and/or personnel to undertake this kind of analysis. The lower-accuracy methods usually cost less because they require a lower level of laboratory training and less expensive equipment. However, in the end, which method is selected will depend on decisions that must be made based on the specific local context.

2.5 SETTING UP LABORATORIES FOR FAECAL SLUDGE ANALYSIS

Laboratories in many fields of research have essential similarities. However, setting up a faecal sludge laboratory needs special attention to health and safety due to the potential for pathogens. Hence, when working with faecal sludge, health and safety is of the highest priorities. This section considers the importance of a strategic workflow, layout, management system, and best-practice health and safety procedures for setting up a laboratory for faecal sludge analysis. It is followed by case studies of established and operational laboratories that have different objectives in different locations, including research laboratories, international collaborations, and a mobile field laboratory for emergency settings.

2.5.1 Faecal sludge laboratory workflow

A workflow is a systematic pattern that stipulates the order in which a sample will move through the space as it is received, prepared, analysed and disposed, until there is data output from that particular sample. Once the samples arrive at the laboratory, an established workflow needs to take place. When receiving biohazardous materials such as faecal sludge, exposure to this type of material must be restricted as much as possible. Sample collection and transport to laboratories is discussed in Chapter 3 and the specific methods for storage, sample preparation and analysis are provided in Chapter 8.

Once received, the faecal sludge samples pass through a number of steps in designated areas, such as sample intake, storage and preparation before reaching the analytical areas (Figure 2.15). By ensuring that these areas are systematically organised and the bulk sample movement within the laboratory is restricted, this will thereby limit the exposure of personnel to pathogens.

Workflow also needs to be considered during the construction, design, or adaptation of a laboratory for faecal sludge analysis. This allows a dedicated sample-receiving area to be placed adjacent to the storage and sample preparation spaces. ‘Clean’ rooms can be included to accommodate precision analytical equipment or microbial analysis, and these can be located away from ‘dirty’ areas where samples are received, stored and prepared. Clean rooms are also required for the preparation of chemical reagents and standard concentration solutions to avoid cross-contamination. Dedicated areas for data capture and analysis adjacent to the analytical rooms prevents cross-contamination as laptops and laboratory notebooks are moved between laboratory and office space.

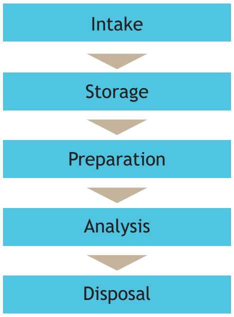


Figure 2.15 Sample processing workflow in a faecal sludge laboratory.

Additional designated areas including an external wash area, chemical storage rooms, equipment storage rooms, personal protective equipment (PPE) storage and changing rooms are recommended. They should be equipped with appropriate handwashing and disinfection facilities for staff prior to leaving the laboratory.

For safety, there must be more than one emergency exit door and they must be accessible at all times. Space must be allocated for safety showers, eye wash, and fire extinguishers (*e.g.* buckets of sand, fire blankets, pressure vessels containing extinguishers), determined by the size of the laboratory and the activities that will be undertaken. Access to safety showers and fire extinguishers must not be obstructed and must be labelled with clear signs.

If a faecal sludge laboratory is being set up as new construction, the systematic workflow will give guidance to the location of required utilities, equipment and designated areas for specialised equipment (Rice *et al.,* 2017). Conversely, if a faecal sludge laboratory is to be retrofitted into an existing space, the laboratory workflow will likely be influenced by the existing layout.

- Taps and sinks should be located in the areas for sample intake, preparation and analysis. They must be located in a safe manner to prevent splashes on nearby electricity power points. A water connection must also be available for safety showers and a basin near the main exit door. If possible, there should be drains on the floors that are linked to the sewerage system.

- Electrical power points must be placed high on the walls, and not at floor level to avoid water leaks, spillages or cause tripping hazards. The number and location of power points will be determined by the analytical equipment required. The switchboard for all the power points must be clearly labelled and should be easily accessible in an emergency.
- Space should be allocated for a gas cylinder storage area that is separated from the main working areas in the laboratory. Gas cylinders must be secured and stored in a ventilated area, with limited exposure to sunlight and ignition sources.
- Odours in a faecal sludge laboratory come from contained faecal sludge, faecal sludge combustion and from chemicals used during analysis. As such, an extraction system that can remove odours for general laboratory users and the public is important. High efficiency particulate air extraction systems are recommended and are coupled to pathogen filters to improve and maintain air quality in the laboratory.

In addition to the utilities discussed, a laboratory needs appropriate workstations and floors - hard, non-porous and chemically resistant. Furniture such as cupboards should be made of materials easy to disinfect.

2.5.2 Health and safety practices

Safe working practices and a written record of these practices are vital to reduce the exposure of personnel to pathogens in faecal sludge and harmful chemicals in a faecal sludge laboratory. The hierarchy of controls shown in Figure 2.16 should be considered when developing safe working practices. The preferred controls are those closer to the top of the pyramid. For example, a manual handling task could make use of a trolley to eliminate the risk of injury from incorrect lifting techniques. Similarly, a test method that uses hazardous chemicals could be substituted for a test method that uses less hazardous chemicals, if appropriate fume hoods are not in place. Fume hoods and ventilation systems are engineering controls which reduce the risks associated with inhalation of fumes and dust. Administrative controls are procedures designed to keep workspaces clean and form a key part of laboratory management systems. The last line of hazard control for laboratory safety is personal protective equipment (PPE). When dealing with pathogenic samples, laboratory coats, closed footwear, nitrile gloves and goggles form part of the necessary safe working wear. PPE might also be required based on the specific task and this can be determined by carrying out a risk assessment.

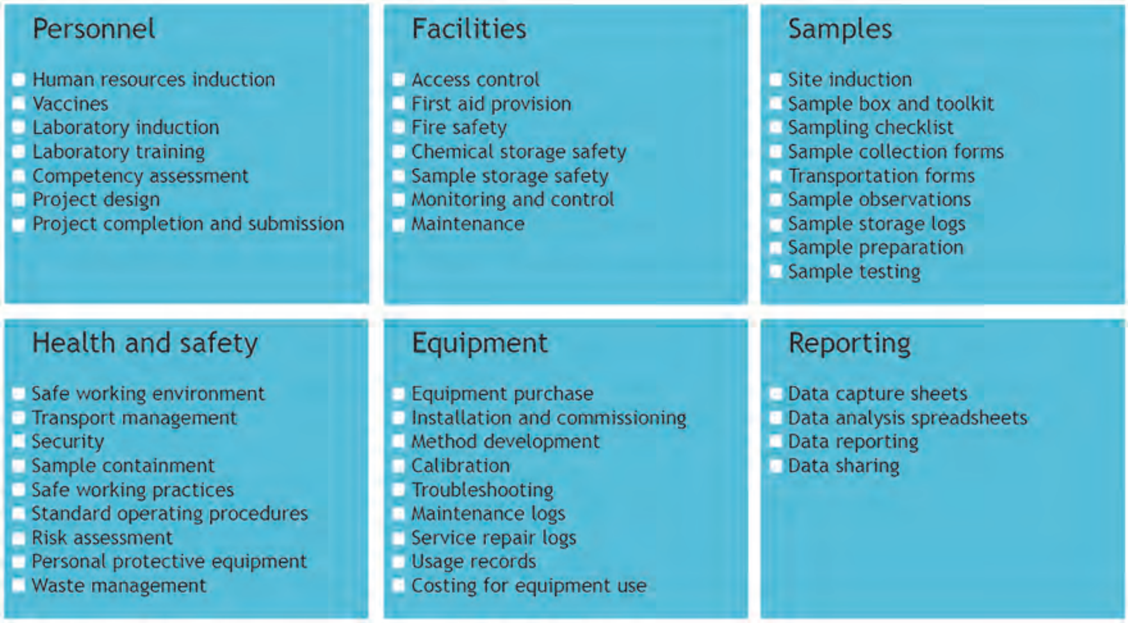
Figure 2.16 Hierarchy of controls for health and safety practices.

All tasks undertaken in the laboratory should have printed copies of standard operating procedures (SOPs) that include risk assessment and management. These documents identify all of the steps needed to carry out a task, the hazards associated with each task, who is at risk from the identified hazards, and the controls that can be implemented to mitigate the risks.

2.5.3 Laboratory management systems

Laboratory management systems establish protocols that govern laboratory processes and maintain a functional system. Laboratory management ensures that proper procedures are adhered to at all times and support is required from all organisational levels in order to ensure safe operation. Laboratories without management systems in place become easily disorganised and cluttered.

Laboratory management systems cover tasks at all levels, as shown in Figure 2.17. Personnel management procedures can vary depending on whether they are suited to staff, students, researchers or visitors. Similarly, facilities management can apply to onsite and offsite laboratories, research test sites and community test sites which can require different procedures.



Personnel

- Human resources induction
- Vaccines
- Laboratory induction
- Laboratory training
- Competency assessment
- Project design
- Project completion and submission

Facilities

- Access control
- First aid provision
- Fire safety
- Chemical storage safety
- Sample storage safety
- Monitoring and control
- Maintenance

Samples

- Site induction
- Sample box and toolkit
- Sampling checklist
- Sample collection forms
- Transportation forms
- Sample observations
- Sample storage logs
- Sample preparation
- Sample testing

Health and safety

- Safe working environment
- Transport management
- Security
- Sample containment
- Safe working practices
- Standard operating procedures
- Risk assessment
- Personal protective equipment
- Waste management

Equipment

- Equipment purchase
- Installation and commissioning
- Method development
- Calibration
- Troubleshooting
- Maintenance logs
- Service repair logs
- Usage records
- Costing for equipment use

Reporting

- Data capture sheets
- Data analysis spreadsheets
- Data reporting
- Data sharing

Figure 2.17 Types of protection provided through laboratory management systems.

When designing laboratory management systems, this should be done in a systematic manner so that processes and procedures are not overlooked. For example, Figure 2.18 shows the laboratory processes from receiving a sample to data distribution. By having procedures written down, there is less confusion about the steps necessary to process samples and where information about existing samples can be found.

Recordkeeping is an important aspect of laboratory management systems. Examples of records are: laboratory induction, laboratory training and competency assessments, sampling field trips, samples received, laboratory daily usage, laboratory analysis, instrument usage, instrument maintenance, and quality controls.

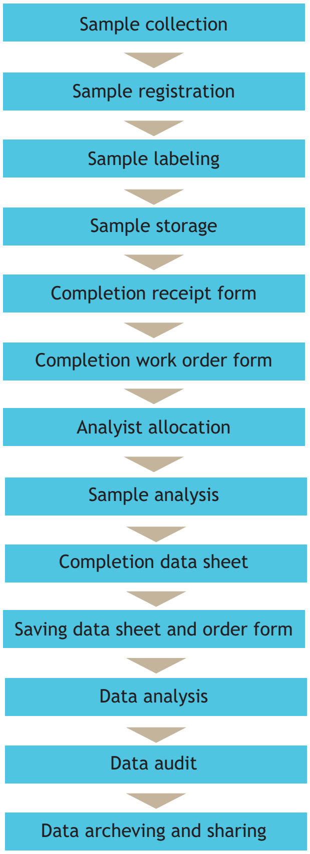


Figure 2.18 A sample management chain from collecting a sample to the results being distributed.

2.5.4 Case studies of global faecal sludge laboratories

Presented here are case studies of established research-based faecal sludge laboratories that are designed to perform analysis and performance evaluation of sanitation systems, also to accommodate teaching, postgraduate research students, local and visiting researchers, and to facilitate trainings. There is also an example of a field-based laboratory that was developed using low-cost alternatives to laboratory equipment, and can be deployed in emergency settings and areas with no laboratory capacity. The final example is of a network of laboratories for knowledge exchange.

Case study 2.1 *UKZN PRG faecal sludge laboratory*

Overview

The Pollution Research Group's (PRG) faecal sludge laboratory is based at the University of KwaZulu-Natal (UKZN), Durban, South Africa and has been operational since the 1970s. The research focus was initially on industrial wastewater and has gradually shifted to water and sanitation with a primary focus on faecal sludge laboratory practices and analysis over the last decade. In 2014 the laboratory undertook a major reconstruction and purchased additional analytical equipment and instruments in order to increase and optimise the laboratory space and management systems.

Focus areas

- Teaching and research of postgraduate students
- Capacity building - training and/or hosting visiting researchers and research students; supporting the development of other sanitation laboratories globally or locally
- Testing and analysis of different faecal sludge samples (Figure 2.19) and developing methods and procedures for faecal sludge analysis and faecal sludge handling procedures
- Testing and evaluating innovative sanitation systems
- Shipping and receiving of faecal sludge samples (Figure 2.20)

Equipment and instruments

The laboratory is fully equipped with analytical instruments used for the purpose of teaching, training, research and capacity building of undergraduate students, postgraduate students, international researchers and practitioners.

Main activities

- Capacity building and collaboration with other laboratories

  An example of the areas of collaboration and support to other laboratories are: improvement of laboratory management systems including health and safety, planning and improvement of laboratory workflows, training and knowledge dissemination of methods and procedures for faecal sludge analysis.

- A collaboration through a Memorandum of Understanding with a local municipality (eThekwini)
  This is a long-term collaboration aiming at a science-based integrated approach, incentives and innovation of the planning activities within the municipality.
- Engineering field testing
  A programme for testing and evaluation of innovative and emerging sanitation prototypes based in the field. The performance is evaluated by researchers and students on a daily basis and the samples are transported, stored and analysed in the UKZN PRG laboratory.

Figure 2.19 Preparation of samples for microwave digestion (photo: UKZN PRG).

Figure 2.20 Freeze-drying of faecal sludge samples (photo: UKZN PRG).

Case study 2.2 *IHE Delft faecal sludge laboratory*

Overview

This is a relatively new faecal sludge laboratory, constructed in 2018 at the facilities of IHE Delft, The Netherlands. In this state-of-the-art laboratory, sanitation professionals and academics from all over the world can develop their skills and carry out research on the characteristics, use and end use of faecal sludge.

Focus areas

- Teaching, capacity development and tailor-made training
- Support of laboratory-based research at Master's and Doctoral level.

Equipment and instruments

After a thorough assessment, the equipment that was selected for the new laboratory was either new or complementary to the already existing equipment, in order to expand the current teaching and analytical capacity of the laboratories at IHE Delft.

Laboratory layout

Due to exposure to the potentially hazardous materials and pathogenic microorganisms in the faecal sludge laboratory, necessary health and safety requirements have been introduced at this facility (Section 2.5.2 and Chapter 8). These and other standards and requirements were taken into account while designing the laboratory (Figure 2.21) which consisted of five thematic rooms: (*i*) the entrance area, (*ii*) practicum/lecture room, (*iii*) research/analytical section, (*iv*) helminth eggs analysis room and (*v*) preparation room.

The entrance to the faecal sludge laboratory is the point where students and staff enter (or exit) the laboratory; this area has storage facilities for the health and safety equipment and has hand-washing facilities. It is connected with the main practicum section that is also used as a lecture room designed to accommodate up to 15 students at one time, working in parallel in up to four groups (Figure 2.22).

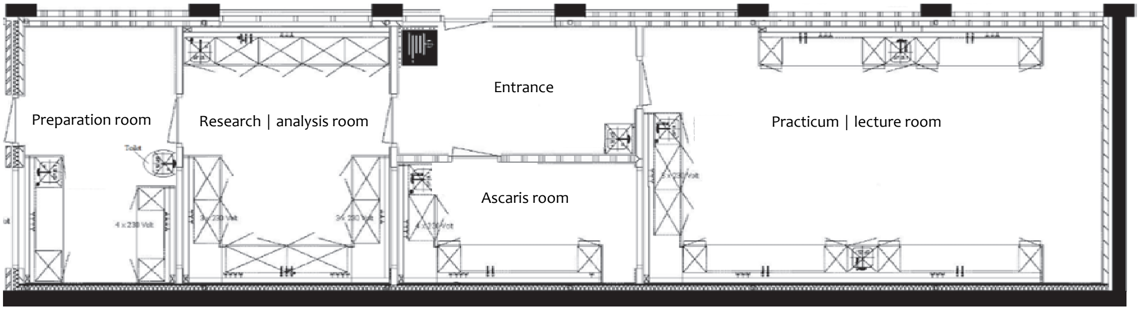


Figure 2.21 Final design of the faecal sludge laboratory at IHE Delft (source: IHE Delft).

Figure 2.22 Practicum/lecture room (photo: IHE Delft).

Figure 2.23 Research section (photo: IHE Delft).

Each group has parallel access to a shared sink, air extraction, electricity and a gas supply connection. This room is equipped with a digital lecture board and the equipment for total and volatile solids analysis. It is designed to be standalone, meaning that teaching can take place while other areas in the laboratory are being used.

Two other rooms can be accessed via the entrance area: the research laboratory and the Ascaris analysis room. The research laboratory is where the analytical equipment such as the analytical balances, Thermal thermogravimetric analyser (TGA) and differential scanning calorimeter (DSC), rheometer, bioreactor and calorimeter with the space and equipment for experimental setups is housed (Figure 2.23).

The Ascaris analysis room is a separate room for helminth eggs and other microbiological analysis. At the back of the faecal sludge laboratory is the sample reception and preparation room, with a separate external entrance for the samples. All samples are handled in this room, before being analysed or used in teaching in other parts of the laboratory.

Main activities

- Teaching and training of students.
  Since opening, the laboratory has been used for teaching the first cohorts of students of the Global Sanitation Graduate School and for the preparation of some of the video materials for the online course that will complement the material presented in this book.

Case study 2.3 NATS AIT faecal sludge laboratory

Overview

With more than 15 years' experience of monitoring, sampling and testing of faecal sludge in Southeast Asia, the NATS laboratory was established in 2016 under the Department of Energy, Environment and Climate Change, School of Environment, Resources and Development, Asian Institute of Technology (AIT), Thailand.

Focus areas

- Support of the field research project on 'Sustainable Decentralised Wastewater Management Systems' that covers assessments of faecal sludge management, non-sewered sanitation systems and implementation of reinvented toilet technologies.
- Further field monitoring and assessing the impacts of the toilet interventions on public health and environmental quality, in particular their compliance with national and/or international standards, *i.e.* ISO 30500 (2018).

Main activities

- Accreditation under ISO/IEC 17025
  The NATS lab has established a laboratory quality management system for analysis of high-strength wastewater and faecal sludge in compliance with ISO/IEC 17025. The accreditation process was applied in late 2017 and is expected to be accredited in late 2020, which will improve the quality control and technical competency in calibration and testing of the laboratory. It is envisaged that the knowledge and experience will be shared with other partner laboratories in the region in support of their accreditation (a voluntary process).
- Support of research students

Laboratory management system

Competency assessments have been implemented annually as well as regular laboratory training and proficiency testing to increase the technical skill and experience for laboratory staff. Quality control and quality assurance systems are in place, and equipment and laboratory glassware are calibrated on an annual basis. The working space of the NATS laboratory is organised in a way to provide a systematic laboratory workflow and best practice for analytical processes. There is a sample receiving area, sample storage, sample preparation, analytical area, cleaning areas for laboratory glassware and an external washing area. The analytical equipment area, chemical storage and clean room for microbiological analysis are positioned away from possible cross-contamination zones.

The NATS laboratory plans to upgrade to a 'Proficiency Testing Centre' for faecal sludge, according to ISO 17043 by supporting the testing process of innovative toilet technologies during product development, supporting performance testing of faecal sludge treatment plants and providing a supporting role for the establishment of other faecal sludge laboratories in the region in the form of training, monitoring and knowledge dissemination.

Figure 2.24 Training on faecal sludge analysis (photo: AIT).

Figure 2.25 External audit in NATS faecal sludge laboratory (photo: AIT).

Case study 2.4 *Eawag faecal sludge laboratories*

Overview

Eawag (the Swiss Federal Institute of Aquatic Science and Technology) was founded as a water and wastewater treatment research institute in 1936, with laboratory analysis of faecal sludge starting over 25 years ago. The department Sandec (Sanitation, Water, and Solid Waste for Development) focuses exclusively on development related research, with the mandate to develop and test methods and technologies that help the world's poorest to access sustainable water and sanitation services.

Focus areas and main activities

- Collaborative research:
  Applied research projects are conducted in collaboration with local universities, municipalities, and NGOs. Over the last 10 years research has been conducted in laboratories in Burkina Faso, Cameroon, India, Malawi, Senegal, Tanzania, Thailand, Uganda, Vietnam, and Zambia (Figure 2.26), in addition to the campus in Switzerland, which is well equipped with state-of-the-art laboratory facilities. Research is conducted with PhD and Master's students to develop fundamental knowledge required for integrated management and technology solutions, such as governing mechanisms of solid-liquid separation of faecal sludge and resource recovery.
- Technology innovations:
  Research development with industrial and implementation partners takes place in the Water Hub in the NEST building on the campus in Switzerland (Figure 2.27). NEST is a modular research and innovation site for testing of new technologies, materials and systems and off-grid, closed-loop technology solutions.
- Training/education:
  Training and education is a core tenet of Sandec, including laboratory training on methods for faecal sludge analysis. All of the Sandec educational resources are available free of charge on the Sandec website, including publications, books, online courses, workshops, newsletters and reference materials[5].

Figure 2.26 Collaborative research project on quantities and qualities of faecal sludge in the laboratory at the University of Zambia in Lusaka (photo: Eawag).

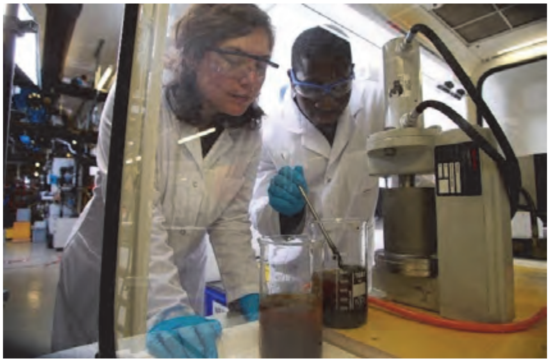


Figure 2.27 Dewatering research conducted by PhD students in the NEST building in Dübendorf, Switzerland (photo: Eawag).

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Case study 2.5 *Faecal sludge field laboratory (FSFL)-Austrian Red Cross and Eawag*

Overview

In 2017 a consortium of the Austrian Red Cross, the University of Natural Resources and Life Sciences, Vienna (BOKU), WASTE Netherlands and Butyl Products Ltd Group, developed a FSFL that is now further supported by the International Federation of Red Cross and Red Crescent Societies (IFRC), Swiss Humanitarian Aid (SDC/HA) and Eawag. The laboratory can be operated almost entirely off-grid with a solar panel and wind turbine.

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[5] www.sandec.ch

Focus areas

- The FSFL was designed as a mobile facility for implementation in emergency settings, and other locations without laboratory capacity.

Main activities

- Methods and equipment have been adapted for these special conditions, and includes analysis of 25 parameters, such as process control parameters (pH, TS, ash, biogas composition, COD), and public health metrics (Helminth eggs, Salmonella, Enterococcus, E. *coli*) (Bousek *et al.,* 2018).
- Selection of cost effective alternatives of laboratory equipment and development of low-cost, low-tech methods for parameters, *e.g.* for COD: using a cooking pot filled with sand as a heating block for the digestion of chemicals in cuvettes.
- The modularity of the FSFL makes it adaptable to many contexts, and the methods will continue to be further refined and tested.

Figure 2.28 A) first deployment of FSFL to Bangladesh in 2019, B) FSFL compactly fits on two pallets for shipping (photos: Eawag and Austrian Red Cross, respectively).

2.5.5 Global Partnership of Laboratories for Faecal Sludge Analysis (GPLFSA)

Experts on faecal sludge analysis recently established the Global Partnership of Laboratories for Faecal Sludge Analysis to address together the challenges and to work towards standardised methods for the characterisation and quantification of faecal sludge from onsite sanitation technologies, including sampling techniques and health and safety procedures for faecal sludge handling. The Partnership also delivers on-campus courses and training and aims to improve communication between sanitation practitioners, provide a comparative faecal sludge database, and improve confidence in the methods and obtained results.

The Partnership currently consists of eleven laboratories: IHE Delft (The Netherlands), UKZN (South Africa), Eawag (Switzerland), CSE and CDD (India), AIT (Thailand), Columbia University (USA), 2iE (Burkina Faso), BITS (India), ENPHO (Nepal) and ITB (Indonesia). More details are provided in Annex 1.

2.6 OUTLOOK

Understanding the purpose of characterisation, the associated faecal sludge properties, and the characterisation process are crucial for both increasing scientific knowledge and making informed decisions for best practices in faecal sludge management. The laboratory methods presented in Chapter 8 are the first step towards establishing standard methods of faecal sludge analysis. However, analytical methods alone are not adequate to provide reliable and repeatable analysis, and must be conducted by adequately trained personal. The background information in this chapter presents material that is necessary prior to conducting analysis of faecal sludge. Four types of faecal sludge, liquid, slurry, semi-solid or solid, are defined, based on total solids content. Their distinction is necessary for implementing the correct steps in the characterisation process, such as appropriate dilutions, and selection of methods (*e.g.* gravimetric or volumetric). However, these types are not reflective of other characteristics such as COD and nutrients, which can also be spread over a wide range of concentrations. An understanding of factors that affect the variability of characteristics along the entire service chain is important in order to understand what analyses are relevant, and must be considered with sampling plans as described in Chapter 3. Selection of appropriate methods for characterisation needs to be based on the available resources, including budget and laboratory capacity. Importantly, all of this must be conducted in an adequately equipped laboratory, with safety measures in place.

As the methods in this book are implemented, and further methods are developed and added to future editions, knowledge of faecal sludge will be greatly improved. Provided in Annex 2 is a link to a database with faecal sludge characteristics reported in the literature, as part of a UKZN PRG study. What is not inherent in the numbers is the innate level of uncertainty and error between the different data sets, due to a lack of standard methods. This highlights the need for development of a global database of characteristics of faecal sludge based on standard methods, so that solutions for faecal sludge management can be pursued with deeper insight, advanced knowledge, and greater confidence.

Figure 2.29 Education and training are key pillars of capacity development in the field of faecal sludge analysis (photo: IHE Delft).

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Figure 2.30 Proper sampling is essential prerequisite for successful faecal sludge characterisation. Photo depicts experts of 500B and Eawag conducting a quantities and qualities (Q&Q) study with field testing of the Volaser in Kohalpur, Nepal, as part of the development of a city sanitation plan (photo: S. Renggli).