Faecal Sludge Management

Editors
Miriam Englund
Linda Strande

Highlights and Exercises

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Text Editing: Claire Taylor
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Authors
(in alphabetical order)

Nienke Andriessen
Miriam Englund
Moritz Gold
Marius Klinger
Christoph Lüthi
Samuel Renggli
Stanley Sam
Linda Strande
BJ Ward

Contributors and reviewers
(in alphabetical order)

Ashanti Bleich
Damir Brdjanovic
Nadège de Chambrier
Guillaume Clair
Kayla Coppens
Marta Fernàndez Cortés
Christopher Friedrich
Pavan Indireddy
Abishek Sankara Narayan
Ariane Schertenleib
Dorothee Spuhler
Fabian Suter
Elizabeth Tilley
Lukas Ulrich
Imanol Zabaleta

Foreword

The book 'Faecal Sludge Management: Systems Approach for Implementation and Operation' was first published in 2014 and has since been translated into English, French, Hindi, Marathi, Russian, Spanish and Tamil. It is used by practitioners and universities around the world. Since its publication, the sector has been rapidly growing and adapting to address the need for faecal sludge management. To keep pace with rapid developments, publications are needed that can adapt more quickly during the time required for new books and book editions to be published. Therefore, 'Faecal Sludge Management: Highlights and Exercises' has been developed as a more flexible publication that will be regularly updated together with our online courses, to help fill this gap. The original book presents an integrated systems based approach including technical, planning and management aspects. The highlights and exercises presented here are currently more focused on the technical aspects. However, the content will continue to be expanded with future editions.

The highlights and exercises are largely based on information that was put together for the production of our online courses. It is a compilation of highlights within each topic, together with exercises to test the users' gained knowledge. Each of the chapters can be used directly in curriculums, training courses or workshops, and can be adapted to fit the context. The goal of the exercises is to start discussions, develop critical thinking, and evaluate learning of material.

It is important to note that this exercise book is not intended to be used as a guideline or as a stand-alone reference, but to be used as a companion guide to existing publications and online courses. Achieving city-wide inclusive sanitation will require faecal sludge management solutions for every scale, for intermediate and permanent standalone solutions, and in combination with sewer-based systems. Hopefully an integrated and adaptive planning mindset, together with an engineering-design approach, will help facilitate sustainable solutions that can be adapted to local contexts.

The learning objectives of this book include:

- Understanding the importance of faecal sludge management, and what is currently lacking;
- Knowing the fundamentals of an integrated approach to faecal sludge management that includes engineering, management and planning;
- Identifying the information required for the design and selection of technologies;
- Understanding management and planning approaches that help to ensure sustainable solutions;
- Being aware of current research and innovations in faecal sludge management;
- Knowing how to approach the implementation of faecal sludge management solutions.

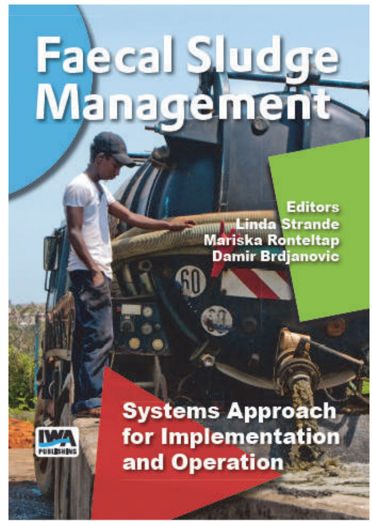
This book has five sections, general introduction, overview of fundamentals for design and selection of treatment technologies, established treatment technologies, planning and management, and current innovations in faecal sludge management. Each of the chapters has the following structure;

- Chapter learning objectives
- Additional resources for the specific topic
- Highlights including a general introduction, and overview of how to apply the topic
- Theoretical examples and case studies
- Exercises

Companion materials for the use of this book

The target audience of this book includes students and practitioners in the field who are or will be designing, planning, promoting, or managing faecal sludge management (FSM) systems. The book provides a comprehensive approach that includes an overview, design guidelines of treatment technologies, important considerations of operations and maintenance for successful operation of implemented technologies, and a planning approach so that all the necessary requirements are met to ensure a long-term, sustainable system. The book assumes the reader has basic knowledge of sanitation and wastewater treatment.

Available free of charge at
www.sandec.ch/fsm_book



This course starts with an overview of what faecal sludge is and introduces you to the engineering fundamentals and required information for the design and selection of technologies. Sanitation solutions are prone to failure if an integrated planning approach that includes stakeholder involvement and the development of appropriate institutional, management and financial arrangements is not implemented. The course therefore dedicates a complete week to presenting the full picture, in addition to the technology, that needs to be considered for sustainable solutions. It concludes with a focus on current research and innovations in technologies, in order to provide an understanding of the most up-to-date options. The course is available in English, with French, Portuguese, and Spanish subtitles.

Available free of charge at
www.eawag.ch/mooc

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Chapter 1.1

What is faecal sludge?

Miriam Englund and Linda Strande

Learning objectives

- Distinguish between types of faecal sludge, and wastewater and excreta
- Name the factors influencing characteristics of faecal sludge
- Name the main constituents of faecal sludge related to treatment

Textbook

Available at www.sandec.ch/fsm_book

- Strande, L., Ronteltap, M. and Brdjanovic, D. (2014). *Faecal Sludge Management - Systems Approach for Implementation and Operation.*

Free online course (MOOC)

Available at www.eawag.ch/mooc

- *Introduction to Faecal Sludge Management.* MOOC series by Eawag and EPFL. Modules 'The global situation' and 'What is faecal sludge'.

Further Eawag-Sandec publications

Available at www.sandec.ch/fsm_tools

- Englund, M., Carbajal, J.P. and Strande, L., (2018). *Method to Estimate Quantities and Qualities of Faecal Sludge.* Sandec News 2018.
- Englund, M., Carbajal, J.P., Amédé, F., Bassan, M., Thi Hoai Vu, A., Nguyen, V.A. and Strande, L. (In prep). *Modelling quantities and qualities (Q&Q) of faecal sludge in Hanoi, Vietnam and Kampala, Uganda for improved management solutions.*
- Gold, M., Harada, H., Therrien, J.D., Nishida, T., Cunningham, M., Semiyaga, S., Fujii, S., Dorea, C., Nguyen, V.A. and Strande, L. (2017). *Cross-country analysis of faecal sludge dewatering.* Environmental Technology, 1-11.
- Schoebitz, L., Bischoff, F., Ddiba, D., Okello, F., Nakazibwe, R., Niwagaba, C.B., Lohri, C.R. and Strande, L. (2016). *Results of faecal sludge analyses in Kampala, Uganda. Pictures, characteristics and qualitative observations for 76 samples.* Eawag-Sandec.
- Strande, L., Schoebitz, L., Bischoff, F., Ddiba, D., Okello, F., Englund, M., Ward, B.J. and Niwagaba, C.B. (2018). *Methods to reliably estimate faecal sludge quantities and qualities for the design of treatment technologies and management solutions.* Environmental Management, 223, 898-907.

Additional resources

- Henze, M., van Loosdrecht, M.C., Ekama, G.A. and Brdjanovic, D. (2008). *Biological wastewater treatment.* IWA Publishing.
- Metcalf & Eddy. (2014). *Wastewater Engineering: Treatment and Resource Recovery.* 5th edition, McGraw-Hill, New York.
- Tayler, K. (2018). *Faecal sludge and septage treatment – a guide for low and middle income countries.* Rugby, UK, Practical Action Publishing.
- Von Sperling, M. and de Lemos Chernicharo Augustos, C. (2005). *Biological Wastewater Treatment in Warm Climate Regions.*
- World Health Organization. (2017). Progress on drinking water, sanitation and hygiene: 2017 update and SDG baselines.

Introduction

Globally, over one-third of the world's population is served by onsite sanitation technologies. Faecal sludge is defined as what accumulates in onsite sanitation technologies. The following is the definition of faecal sludge from the book, *Faecal Sludge Management - Systems Approach for Implementation and Operation:*

> Faecal sludge comes from onsite sanitation technologies, and has not been transported through a sewer. It is raw or partially digested, a slurry or semisolid, and results from the collection, storage or treatment of combinations of excreta and blackwater, with or without grey water. Examples of onsite technologies include pit latrines, unsewered public ablution blocks, septic tanks, aqua privies, and dry toilets. Faecal sludge management includes the storage, collection, transport, treatment and safe enduse or disposal of faecal sludge. Faecal sludge is highly variable in consistency, quantity, and concentration.

The differences between excreta, faecal sludge and wastewater

To better understand what faecal sludge is, it is helpful to look at the definitions for excreta, faecal sludge and wastewater, and understand how they are different, as illustrated in Figure 1.1.1. **Excreta** is urine and faeces. **Faecal sludge** is composed of excreta, but also includes anything else that goes into an onsite containment technology, for example flushwater, cleansing materials and menstrual hygiene products, grey water (bathing or kitchen water, including fats, oils and grease), and solid waste. Faecal sludge is stored onsite, and is periodically collected and transported to a treatment plant, followed by safe disposal or reuse. **Wastewater,** on the other hand, also contains excreta, but it is transported via a sewer, which conveys it to a treatment plant. Hence, wastewater and faecal sludge have entirely different service chains before they arrive at treatment plants; faecal sludge management relies on a complex service chain that depends on interactions between people at every step. Wastewater can also contain stormwater runoff.

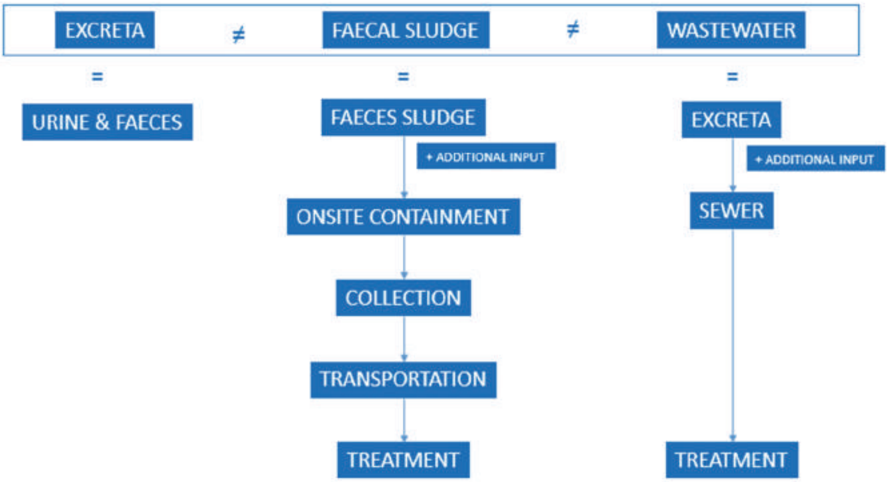

Figure 1.1.1 Illustrating the difference between excreta, faecal sludge and wastewater. Taken from the MOOC *Introduction to Faecal Sludge Management.*

Different types of sludge

As illustrated in Figure 1.1.2, there are several different types of sludge, which also have different characteristics. For wastewater sludge, examples include the sludge that is in the sewer (or sewerage), or types of sludge from wastewater treatment plants (e.g. waste activated sludge, stabilisation pond sludge, anaerobically digested sludge or biosolids). Types of faecal sludge from onsite containments that are not connected to sewers include septic tanks and pit latrines. Septic tank sludge is also commonly called septage, and includes sludge, scum and supernatant. Faecal sludge has a wide definition, since it refers to what accumulates in any type of onsite sanitation technology, as long as it is not connected to the sewer. Terminology can vary depending on geographic location, professional background or preference, but different terminology does not change the actual definition or characteristics.

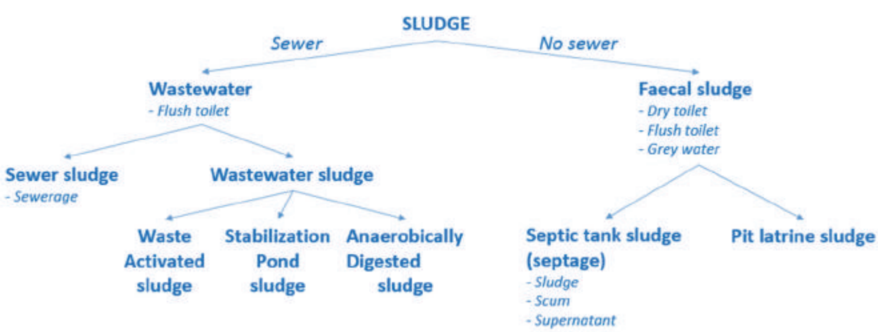

Figure 1.1.2 Illustrating examples of types of sludges (not meant to be all inclusive). Taken from the MOOC *Introduction to Faecal Sludge Management.*

Factors affecting the variability of faecal sludge characteristics

Faecal sludge characteristics are highly variable due to many factors. Some of the factors influencing the variability of faecal sludge characteristics are illustrated in Figure 1.1.3, and the following are some examples:

- **temperature** can affect rates of degradation
- **containment type** such as a lined pit latrine with no overflow, or a septic tank with an overflow for supernatant, can affect concentrations
- **additional inputs** such as grey water can affect concentrations, or kitchen waste can affect fats, oils and grease, or garbage can affect volumes
- **retention time** can range from days to years, and can affect the level of stabilization
- **emptying practices** such as fully or partially emptied, or if water was added to help sludge removal, can affect concentrations and stabilization
- **treatment performance** such as for septic tanks that are designed for solid-liquid separation, can affect concentrations of solids in the septic tank and in the supernatant
- **construction quality** such as a septic tank that was poorly constructed with an impervious bottom, or an unlined pit latrine that collapses, can have multiple effects on sludge characteristics
- **groundwater** such as infiltration into pit latrines, or exfiltration of faecal sludge, can affect concentrations.

Figure 1.1.3 Parameters that can affect faecal sludge characteristics. Taken from the MOOC *Introduction to Faecal Sludge Management.*

Another reason why faecal sludge is highly variable when it is delivered to treatment is that it is emptied batch-wise from individual households or commercial enterprises, each of which could have different usage patterns. This is in contrast to wastewater, which is relatively more homogenized during transport in the sewer. This is demonstrated in Figure 1.1.4, which shows influent COD values for faecal sludge and wastewater during 2014 at the Lubigi faecal sludge and wastewater treatment plant in Kampala, Uganda. The faecal sludge is much more variable, by up to two orders of magnitude.

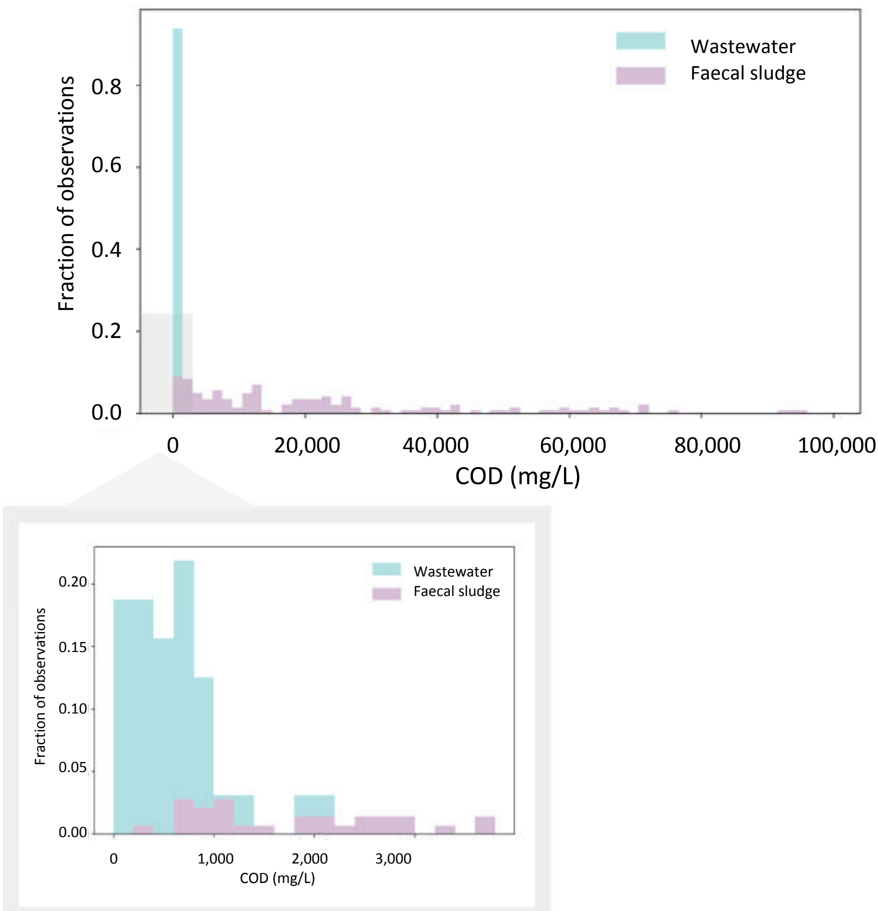

Figure 1.1.4 **Influent COD values from the Lubigi faecal sludge and wastewater treatment facility in Kampala, Uganda, during 2014.**

Figure 1.1.5 illustrates what this variability can look like with the example of faecal sludge samples taken in Dakar, Senegal at the Cambérène faecal sludge and wastewater treatment plant during 2018. All of the samples in this picture were taken from similarly constructed cess pits (commonly referred to in Dakar as septic tanks).

Figure 1.1.5 Illustration of the variability present in faecal sludges. © Ward, B.J. Eawag-Sandec

Example 1.1.1 Faecal sludge variability

In Hanoi, Vietnam, and in Kampala, Uganda in 2013 and 2014 studies were carried out to better understand the variability of faecal sludge at a city-wide scale, and factors that could be used as predictors of the characteristics of faecal sludge when it arrives at treatment plants (Englund *et al.*, submitted; Strande *et al.*, 2018). The raw data are presented in Figure 1.1.6 and Figure 1.1.7. In Hanoi, the data represents samples from 60 household septic tanks, whereas in Kampala the data represents 180 samples taken from multiple origins, including households, commercial enterprises, schools, and public toilets, and also from different types of containment, meaning types of pit latrines and septic tanks. The results illustrate how characteristics of faecal sludge are highly variable coming from the same type of containment, across one city with similar usage patterns, and even more so from city to city. Therefore, it is very important to evaluate quantities and qualities of faecal sludge for each specific context. For more information on these studies, see (Englund *et al.,* submitted; Strande *et al.*, 2018).

Hanoi: 60 samples of household septic tanks

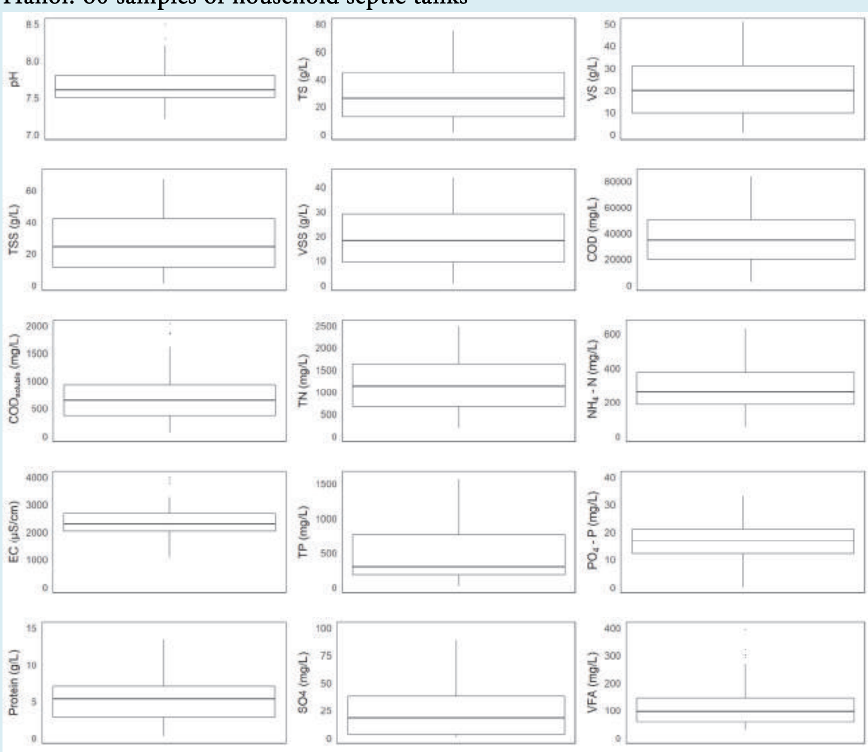

Figure 1.1.6. Characteristics of faecal sludge in Hanoi, Vietnam, from 60 samples taken in 2013 and 2014 (figure taken from Englund *et al.,* submitted).

Kampala: 180 samples of mixed origin and containment types

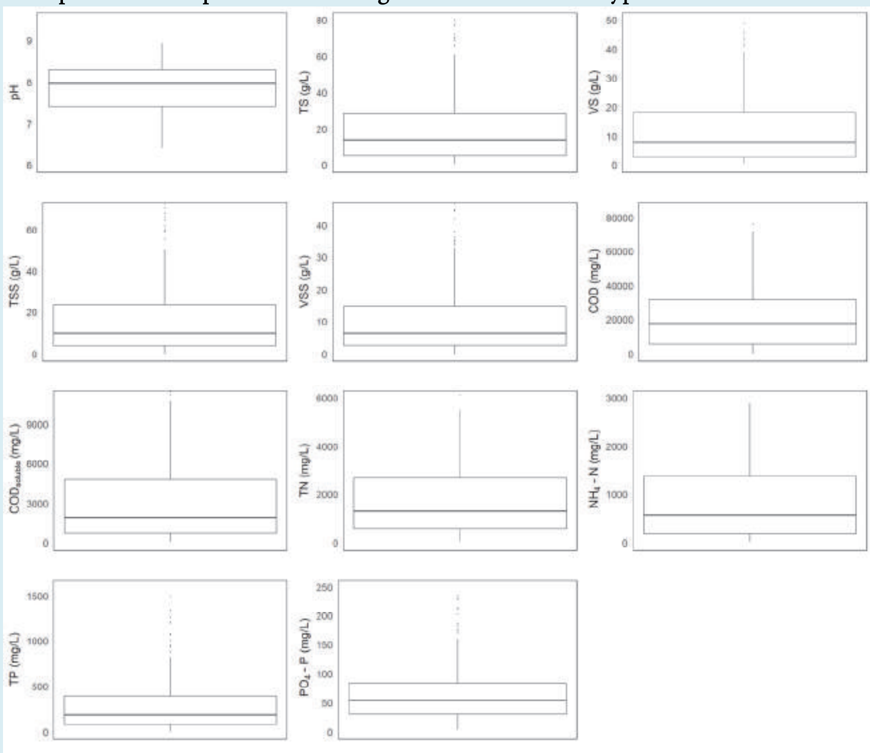

Figure 1.1.7. Characteristics of faecal sludge in Kampala, Uganda, from 180 samples taken in 2013 and 2014 (Strande *et al.,* 2018).

Exercises

1. List benefits of faecal sludge management, benefits of sewer-based solutions, and benefits of hybrid approaches to city-wide inclusive sanitation.
2. A third of the world's population sanitation needs are fulfilled by faecal sludge management. In what range of income level countries can you find faecal sludge management? Choose from the alternatives below (a-c), multiple answers are possible.
   a) Low-income countries
   b) Middle-income countries
   c) High-income countries
3. What is the difference between excreta, faecal sludge and wastewater?

4. Explain the difference between sewered and onsite sanitation systems.
5. Read the following statements and discuss how characteristics of faecal sludge could be affected.
   a) It is the rainy season, and a community has unlined pit latrines in sandy soils.
   b) A septic tank was initially only connected to a toilet, but has now also been connected to a shower and sink in the bathroom.
   c) A pit latrine that was originally built for one family is now being used by 25 people due to increasing population density.
   d) An ablution block at a school is connected to an ABR (anaerobic baffled reactor), and since recently the grey water from the school kitchen has also been treated in the ABR.
   e) Pit latrines service the employees at a factory, which are emptied every other week.
6. What are reasons why faecal sludge may include more solid waste than wastewater?
7. The faecal sludge management service chain is illustrated below (©Eawag-Sandec). Name each of the steps, and briefly explain.

8. Two engineers are discussing the quantities of faecal sludge in a community in order to properly size a new treatment plant. One engineer is of the opinion that per capita urine and faeces production should be used. The other that the total volume of faecal sludge that is emptied from onsite containments should be used. Who do you agree with, and why?
9. Many practitioners that are new to faecal sludge management initially have the perception that faecal sludge coming from dry toilets is very thick. Can you explain why this is not necessarily true, and what they should expect from faecal sludge characteristics?
10. Briefly list and describe the parameters that affect faecal sludge characteristics during containment?

Chapter 1.2

Engineering design approach for design of treatment technologies

Miriam Englund and Linda Strande

Learning objectives

- Explain why an integrated approach to city-wide faecal sludge management requires planning, management and technology
- Explain why a sound engineering design approach is required for the design and selection of treatment technologies
- Think through the steps for an engineering design approach in a given context

Textbook

Available at www.sandec.ch/fsm_book

- Strande, L., Ronteltap, M. and Brdjanovic, D. (2014). *Faecal Sludge Management - Systems Approach for Implementation and Operation*.

Free online courses (MOOCs)

Available at www.eawag.ch/mooc

- *Introduction to faecal sludge management*. MOOC series by Eawag and EPFL. Module 'Systems Based Approach'.
- *Planning & design of sanitation systems and technologies*. MOOC series by Eawag and EPFL.

Further Eawag-Sandec publications

Available at www.sandec.ch/fsm_tools

- Englund, M., Carbajal, J.P. and Strande, L. (2018). *Method to Estimate Quantities and Qualities of Faecal Sludge.* Sandec News 2018.
- Strande, L., Schoebitz, L., Bischoff, F., Ddiba, D., Okello, F., Englund, M., Ward, B.J. and Niwagaba, C.B. (2018). *Methods to reliably estimate faecal sludge quantities and qualities for the design of treatment technologies and management solutions.* Environmental Management. 223, 898-907.
- Strande, L., Gold, M., Schoebitz, L. and Bassan, M. (2016). *Engineering Approach for Selection and Design of Treatment Technologies*. Sandec News 2016.

- Strande, L., Englund, M. and Carbajal, J.P. *Quantities and Qualities (Q&Q) of Faecal Sludge for Planning and Management.* In preparation as a chapter of 'Methods for Faecal Sludge Analyses' (IWA Publication). Velkushanova, K., Strande, L., Ronteltap, M., Koottatep, T., Brdjanovic. D. and Buckley, C. (editors).
- Tilley, E., Ulrich, L., Lüthi, C., Reymond, P. and Zurbrügg, C. (2014). *Compendium of Sanitation Systems and Technologies.* 2nd edition. Dübendorf, Switzerland, Swiss Federal Institute of Aquatic Science and Technology (Eawag). www.sandec.ch/compendium

Additional resources

- Blackett, I. and Hawkins, P. (2017). *FSM Innovation Case Studies - Case Studies on the Business, Policy and Technology of Faecal Sludge Management (*2nd edition*)*. Bill & Melinda Gates Foundation, Seattle, USA, ISBN 978-1-5136-2513-3.
- Tayler, K. (2018). *Faecal sludge and septage treatment – a guide for low and middle income countries.* Rugby, UK, Practical Action Publishing.
- Metcalf & Eddy (2014) *Wastewater Engineering: Treatment and Resource Recovery.* 5th Edition, McGraw-Hill, New York.

Introduction

When implementing faecal sludge management, planning is one of the most essential components of sustainable solutions. Ensuring that faecal sludge management operates smoothly requires a complex service chain that depends on interactions among people at every step.

When working on solutions for any step in the service chain, decision makers, design engineers, and practitioners should make decisions based on an integrated design approach. ***Engineering design*** is the formulation of a plan to build a product (or infrastructure) with ***a specific treatment objective and/or performance goal***. For wastewater treatment, that usually means designing treatment to meet effluent and solids requirements. Unfortunately, for faecal sludge management, currently there is frequently still a lack of appropriate regulations and guidelines, and too often decisions are made more on factors such as available funding (either by trying to spend all of it, or to be as cheap as possible), and not on the final treatment objectives. The engineering design approach provides a systematic way of setting appropriate treatment objectives in the lack of a clear regulatory framework.

The three steps of the engineering design approach for faecal sludge treatment plants that are briefly introduced in this chapter are:

1) Setting treatment objectives based on the final enduse or disposal option
2) Estimating quantities and qualities (Q&Q) of incoming faecal sludge
3) Evaluating selection of management solutions and treatment technologies

A lack of regulations for the treatment of faecal sludge (solid and liquid fractions) complicates the definition of treatment objectives and performance goals. One way to address this is to design for resource recovery, as the use of treatment products will define goals that need to be met to protect public and environmental health. The need for institutional and regulatory frameworks to stimulate resource recovery, and other aspects of the enabling environment, are part of sustainable implementation and city-wide sanitation planning. The engineering design approach is an iterative process that needs to take into account the dynamics of the full faecal sludge management chain and enabling environment.

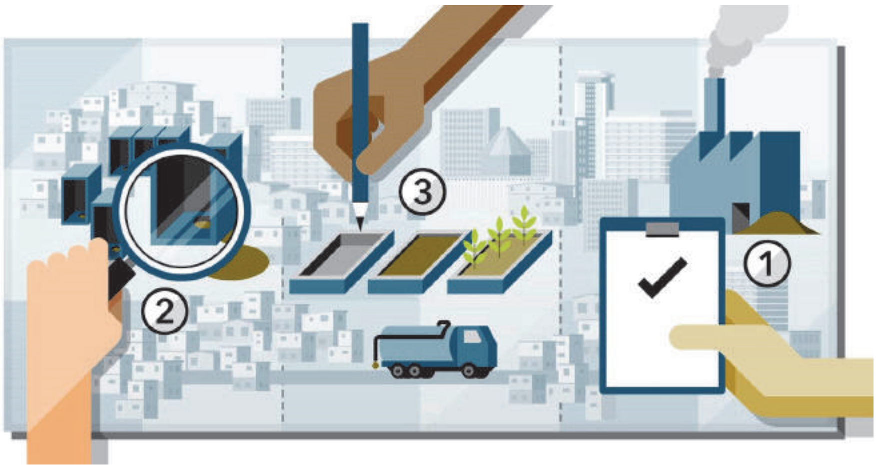

Figure 1.2.1 **The engineering design approach to faecal sludge management: (1) first, treatment objectives and performance goals are set; (2) then quantities and qualities (Q&Q) of incoming faecal sludge are estimated; and (3) finally a selection of treatment technologies or management solutions is evaluated. Figure supplied from Strande *et al.,* (2016).**

Step 1

First, options for the final enduse or disposal of treated faecal sludge are evaluated. Based on the enduse, treatment objectives and corresponding performance goals are defined that can be used to work backwards, to inform design variables for the treatment technology that can achieve these goals. For example, pathogen inactivation for a certain treatment product, and an acceptable level of pathogen reduction that can be measured to ensure the treatment objective. Refer to chapter 2.4 for the Market-Driven Approach (MDA) to help select types of resource recovery options and corresponding faecal sludge treatment products. It is important to keep in mind that over-designing treatment technologies wastes money and resources, while under-designing does not provide adequate protection of human and environmental health.

Step 2

Second is developing an understanding of the Q&Qs of faecal sludge that will be arriving at the treatment facility. Based on these estimates, technologies can be selected and sized appropriately. For more information on methods to determine Q&Qs of faecal sludge at community to city-wide scales relevant for the design of treatment and management solutions, refer to the references provided in the box at the beginning of this chapter.

Step 3

Based on the defined treatment objectives and the estimated incoming Q&Qs of faecal sludge, feasible technology and management options can be selected. Section 4 of this book introduces system-based planning and management aspects of an integrated approach that help build the foundation of long-term successful systems. To select the most appropriate options, factors such as existing infrastructure and services, available skills and capacities, legal requirements and regulations, social acceptance and norms, operation and maintenance, and financial viability need to be considered. Various trade-offs will exist among all these factors, and it is important to find a balance together with all stakeholders.

Example 1.2.1 The engineering design approach

In a city in India it has been decided to build a new faecal sludge treatment plant on available land next to an existing wastewater treatment plant. Currently the wastewater treatment plant is under capacity, and the two treatment plants will be operated in parallel by the same team of staff. There are existing companies that provide collection and transport services, but currently, they are dumping the collected faecal sludge illegally, directly into a stream that flows through the city. Therefore, the first objective is to end unsafe dumping in the environment, and ensure safe delivery to the faecal sludge treatment plant.

An assessment of the initial situation (chapter 4.2) including the Market-Driven Approach (chapter 2.4), the SPA-DET approach to quantities and qualities (Q&Q) of faecal sludge, and an evaluation of the capacity of the existing wastewater treatment plant (chapter 3.6), identified that the wastewater treatment plant is only at 50% of its design capacity, and that brick factories in the city lack adequate fuel. The factories are interested in buying dried faecal sludge to supplement their existing sources of fuel. To meet this need, the treatment objective is dewatering of the faecal sludge, followed by drying. The treatment objective for the liquid streams from the dewatering step, is to enable adequate treatment in the neighbouring wastewater treatment plant for disposal as discharge to the river. Note, that in this example the treatment objective of the faecal sludge treatment plant effluent is to meet the wastewater influent characteristics, for a successful co-treatment. The national standards are presented in Table 1.2.1, and they will be enforced.

Table 1.2.1 Example of discharge standards.

Parameter	Discharge standard
TSS	100 mg/L
BOD	30 mg/L
COD	250 mg/L
Total coliform	1,000 CFU/100mL

Results of the SFD (shit flow diagram) are that 60% of excreta in the city is not safely managed. 75% of the city is not served by the sewer, and has household-level water connections and septic tanks, resulting in a relatively dilute faecal sludge. Based on the preliminary assessment and Q&Q study, the expected median values for faecal sludge that will be delivered to the new treatment plant are presented in Table 1.2.2.

Table 1.2.2 Summary of expected incoming faecal sludge.

Parameter	Value (median values)
TS	11 g/L
TSS	7 g /L
SVI	50 mL/g TSS
Expected incoming faecal sludge	30 m^3/day

Based on the assessment of the initial situation, the faecal sludge treatment plant will be designed to treat 30 m^3/day, and the treatment capacity and expected growth will be revaluated annually. The following treatment chain will be implemented: discharge point with screening, settling-thickening tanks, with supernatant going to the wastewater treatment plant and the settled sludge being pumped to unplanted drying beds once a week. The leachate from drying beds will also go to the wastewater treatment plant, and the dewatered sludge will be pelletized and then air-dried on drying racks.

Settling-thickening tanks were selected to reduce the total required footprint of the treatment plant, based on the relatively dilute faecal sludge and the results of the SVI tests. Based on the estimated incoming TSS values, two 30 m^3 settling-thickening tanks are required. However, the size will be increased to accommodate expected increases in treatment plant capacity, which will be re-evaluated annually. For details on how to size a settling-thickening tank refer to chapter 3.2.

Unplanted drying beds were selected as a relatively easy to operate and maintain treatment technology, and the available land area. Pumping sludge once a week to the beds should be feasible, even with the rolling power outages. Six beds will be constructed, with an area of 280 m^2. This is based on an assumed hydraulic loading rate of 0.3 m, and a solid loading rate of 250 kg TS/m^2.yr. The surface area required will be determined based on the incoming TS from the settling-thickening tank to the unplanted drying beds; an estimate of 60 g/L was used. For details on how to size an unplanted drying bed, refer to chapter 3.3.

Exercises

1. If you are working in a city that has clear sludge disposal and effluent standards for faecal sludge treatment plants, could you still apply the engineering design approach?
2. What are the three steps of the engineering design approach?
3. For faecal sludge management to operate smoothly it requires interactions amongst stakeholders at every step of the service chain. List stakeholders that are relevant to the engineering design approach.
4. In the faecal sludge management context explain
   a) Planning
   b) Management
   c) Technology
5. Explain why an **integrated approach** to community and city-wide faecal sludge management (including planning, management and technology) is important.
6. Describe the concept of the engineering design approach.

Assignment

Faecal sludge management in Wulugu, Fakeland

Tasks

You are an engineering consultant and have been hired by the government to propose a concept for a second faecal sludge treatment plant in Wulugu city. Use your expertise and apply the engineering design approach to answer the questions at the end of the case study, based on the information presented. The information in this case study is based on information collected in a city in West Africa; however, some information has been modified.

City profile

Wulugu is a city in the eastern part of Fakeland, 450 km from the capital. Wulugu is the fourth largest city in Fakeland in terms of population and economy. 20 years ago, the population was 335,000. Currently, the population is estimated to be 949,200 inhabitants.

Climatic conditions

Wulugu region is characterized by a transitional tropical climate, meaning there are two well-differentiated seasons: the rainy season (May to October) and the dry season (November to mid-April).

Economic profile

Wulugu is the economic hub of the eastern region of Fakeland. Mining and construction companies are the two biggest formal employers. A large-scale cement factory is located 40 km south of the city centre, and there are also several large-scale brick production companies. The cement factory feeds fuels automatically into kilns with a blower device. Both use any available form of solid fuel to meet their energy demand, which is greater than 40 tons/day. There are numerous poultry and cattle farms in the region, and the majority of the residents also practise subsistence farming in small urban plots. In low-income areas of the city, wood collected from the surrounding forest is the major cooking fuel.

Sanitation stakeholders

The national sanitation corporation, **FNSC,** is a state company that is responsible for ensuring adequate sanitation. The **city council** and FNSC are collaborating to improve and support good sanitation practices in the area, for example, on how to safely manage manual emptying and to reduce informal operations. There is an **emptying association** of four private service providers with a total of 10 trucks, customers call the companies when their containment fills up, and they have also started working in collaboration with FNSC and the city council to formalize the sector.

Existing sanitation situation

A recently completed SFD (shit flow diagram) reported 70% of the excreta in the city is unsafely managed, with 100% onsite sanitation. There is currently one faecal sludge treatment plant with a capacity of 250 m^3/day, but it is overloaded by at least 20%. The treatment plant is too difficult for trucks in many parts of the city to reach during the day due to traffic congestion, which results in illegal dumping directly in the urban environment. 65% of the population are using pit latrines, and 35% septic tanks. FNSC and the city council are subsidising construction of septic tanks, rather than pit latrines, because they feel it will protect groundwater sources, and have developed a guideline for septic tank construction and operation and maintenance.

A Q&Q study was conducted four years ago prior to the design of the existing faecal sludge treatment plant. The faecal sludge in Wulugu has a relatively high TS, and a relatively low VS fraction, and is mainly dark brown in colour. Based on the SFD, Q&Q study, transect walks, field observations from the existing illegal dumping sites that are most commonly used, and the volumes of faecal sludge that are currently being discharged at the existing faecal sludge treatment plant, an accumulation rate of 95 L/cap.year was established for septic tanks and 50 L/cap.year for pit latrines. These accumulation rates were developed based on weighted averages taking into account different accumulation rates for areas with different income level and available water connections. Based on total coverage of pit latrines and septic tanks reported in the SFD, the overall weighted average for the city is 66 L/cap.year.

There is a sanitation master plan, which includes construction of a wastewater treatment plant that will serve 20% of the population within the next five to eight years. There are four public toilets located at central markets, and one at the bus station; all are operated by the private sector. The sludge is also emptied by the mechanical emptying service providers. The public toilets are in a good hygienic and infrastructural state and are frequently used by both women and men. The costs to use the toilet or the urinal are 0.1 US$ or 0.05 US$, respectively.

Collection and transport

It is estimated that 55% of the emptying that is done is by mechanical service providers in the emptying association, and 45% manually, either by service providers, or by households themselves (6%). A recent study has estimated that emptying frequencies are distributed as 15% empty two times a year, 10% empty once a year, 20% empty every second year, and 55% empty every third year or more.

Figure 1.2.2. A truck desludging a household pit latrine.

The emptying service providers report that business is profitable, especially in the rainy season (up to 10 trips a day). The cost of mechanical emptying is 30-60 US$, depending on the volume emptied. Most of the trucks are modified used trucks purchased from operators in the capital city. Since the faecal sludge treatment plant opened three years ago the truck business has tripled.

Treatment and resource recovery

The existing treatment plant was commissioned three years ago, with a capacity of 250 m^3 per day. The primary treatment objective for the faecal sludge treatment plant is solid-liquid separation for resource recovery of faecal sludge in agriculture; however, resource recovery is not yet occurring. For treatment of the liquid fraction from dewatering there are waste stabilisation ponds, and the treated effluent is discharged to a nearby river.

The existing faecal sludge treatment plant is operating 6 days a week (Monday to Saturday) and is open from 7:30 am to 5:30 pm. The peak flows are unknown, but the peak hours are between 8-11am. The total available land area is 40,000 m^2, and the currently operating treatment plant including office space takes up 30% of the total area available.

Monitoring is required by the national environmental protection agency, FAKEPOL. FNSC does their own sampling and laboratory analysis of the effluent from the waste stabilization ponds, and reports these values to FAKEPOL. There are existing national guidelines for discharge into water bodies. There is an initiative from the Ministry of Sanitation and Hygiene to also develop guidelines for the disposal of sludge.

Currently resource recovery is not taking place; however, the long-term plan is to make a fertilizer product with the dewatered sludge. Pelletizing with the addition of nitrogen is being considered, to increase market demand. A study is planned to determine if fertilizer should be marketed to individuals for subsistence farming or to commercial farms.

Based on the provided information answer the following questions, and identify where more information would be useful. There are multiple correct answers.

1. What information in the case study is useful for setting treatment objective(s) and performance goal(s)? Based on this, suggest appropriate treatment objective(s) and performance goal(s).
2. What information should be used to establish quantities and qualities (Q&Q) for the annual evaluation of adequate treatment capacity? Why?
3. What information would be useful to select a location for a second faecal sludge treatment plant? What treatment technologies would you consider? Why?
4. What are the greatest gaps in information in the case study that would be helpful for making more informed decisions on future solutions for faecal sludge management?
5. How would you plan to gather additional data?

Chapter 2.1

Treatment objectives

Miriam Englund and Linda Strande

Learning objectives

- Name different treatment objectives
- Relate health and environmental impacts to treatment objectives
- Understand different levels of appropriate treatment depending on enduse

Textbook

Available at www.sandec.ch/fsm_book

- Strande, L., Ronteltap, M. and Brdjanovic, D. (2014). *Faecal Sludge Management - Systems Approach for Implementation and Operation.*

Free online courses (MOOCs)

Available at www.eawag.ch/mooc

- *Introduction to Faecal Sludge Management.* MOOC series by Eawag and EPFL. Module 'Treatment Objectives'.
- *Planning & design of sanitation systems and technologies.* MOOC series by Eawag and EPFL. Week ´Introduction to sanitation planning & systems approach´.

Further Eawag-Sandec publications

- Tilley, E., Ulrich, L., Lüthi, C., Reymond, P. and Zurbrügg, C. (2014). *Compendium of Sanitation Systems and Technologies. 2nd edition.* Dübendorf, Switzerland, Swiss Federal Institute of Aquatic Science and Technology (Eawag). www.sandec.ch/compendium

Additional resources

- Metcalf & Eddy (2014). *Wastewater Engineering: Treatment and Resource Recovery.* 5th Edition, McGraw-Hill, New York.
- Tayler, K. (2018). *Faecal sludge and septage treatment – a guide for low and middle income countries.* Rugby, UK, Practical Action Publishing.
- Von Sperling, M. and De Lemos Chernicharo Augustos, C. (2005). *Biological Wastewater Treatment in Warm Climate Regions.*
- World Health Organisation (2015). *Sanitation safety planning manual for safe use and disposal of wastewater, greywater and excreta.* Switzerland.
- World Health Organization (2018). *Guidelines on sanitation and health.* Licence: CC BY-NC-SA 3.0 IGO.

Introduction

The main goal of sanitary engineering and faecal sludge management is the protection of public health. The 'f' diagram below depicts faecal-oral routes of contamination, which need to be prevented to reduce health risks and protect public health. The pathways are represented by the 'f' words: faeces, fluids, fields, flies, food and fingers, as shown in Figure 2.1.1. Protection of environmental health is also an important goal, which is closely linked to the protection of public health. Safe disposal is also a goal, and whenever possible resource recovery should be considered, which is covered in more detail in chapter 2.3.

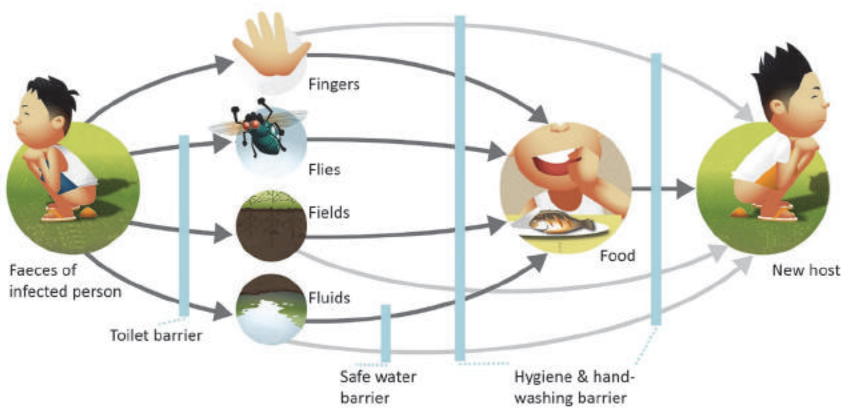

Figure 2.1.1 The 'f' diagram illustrating the infectious transmission pathways of pathogens (adapted from wikipedia.org).

The above mentioned goals can be translated into four main treatment objectives for faecal sludge: dewatering, stabilization, nutrient management, and pathogen inactivation.

Dewatering is important, as faecal sludge is typically over 90% water, and water is cumbersome and expensive to transport. Large volumes of contaminated water can also easily contaminate the environment, so separation of liquids and solids is also important for more effective treatment options.

Stabilization is the process of converting biodegradable organic matter into more stable complex molecules. This is important for treatment, as readily degradable matter consumes significant amounts of oxygen during degradation. If it is directly discharged this can cause environmental damage. For example, in a river it will result in a rapid drop in the dissolved oxygen in the water, which will create anaerobic conditions that can kill the aquatic organisms. Stabilization also results in nutrient stabilization, as ionic forms are taken up into the organic matter, meaning they are not readily leached out and available for plant growth. Stabilization normally also results in a reduction of the odour.

The nutrient management aspect is important to preserve beneficial nutrients for resource recovery options, and to prevent environmental contamination. As mentioned, stabilization is also important for nutrient management. Environmental impacts from nutrients include eutrophication and algal blooms in surface waters, and contamination of drinking water. Moreover, nutrients are of relevance for resource recovery in agriculture.

As illustrated by the 'f' diagram, pathogen inactivation is important to prevent direct contact or indirect exposure to pathogens. The appropriate level of pathogen inactivation during treatment processes will depend on the intended enduse, and on possible routes of exposure. The treatment objectives should not be prioritized; however, pathogen inactivation is crucial for the protection of public health. There are seven mechanisms for pathogen inactivation that occur during treatment; age, predation, starvation, temperature, moisture, pH, and solar radiation or ultraviolet light; refer to chapter 2.2 for more information about how to inactivate pathogens.

The transmission cycle of pathogens can be interrupted by putting barriers in place to block transmission paths and prevent cycle completion. The first barrier for beneficial use is provided by the level of pathogen inactivation achieved through the treatment of faecal sludge. A selection of further post-treatment barriers, prior reusing treated solid and liquid streams, may include:

- restriction of use on crops that are eaten raw,
- withholding periods between application and harvest to allow pathogen die-off,
- drip or subsurface irrigation methods,
- restricting worker and public access during application,
- use of personal protective equipment,
- safe food preparation methods such as thorough cooking, washing or peeling.

When considering the risk of infection, all the potential exposure groups should be accounted for which can be broadly categorized as workers and their families, the surrounding communities and the product consumers. For more information on a multi-barrier risk-based approach to ensure adequate protection of public health, refer to the new WHO Guidelines on Sanitation and Health (2018), the Sanitation safety planning manual for safe use and disposal of wastewater, greywater and excreta (2015), and the Sanitation Safety Planning Module in Sandec's MOOC on Planning & design of sanitation systems and technologies.

Example 2.1.1 When national guidelines are not available

World Health Organization. (2018). *Guidelines on sanitation and health.*

The importance of faecal sludge management is rapidly gaining worldwide acknowledgement. However, in many locations, policies and guidelines are not yet in place. Therefore, the World Health Organisation has developed guidelines that can be used by national and local authorities as a starting point when building their own guidelines, to ensure adequate treatment objectives are defined, regulated and enforced. These guidelines can also be used as treatment objectives by practitioners when designing for management and treatment solutions in the absence of other standards.

The purpose of the guidelines is to protect public health by promoting safe sanitation systems and practices. They seek to support authorities and practitioners to identify health risks and ways to manage them effectively.

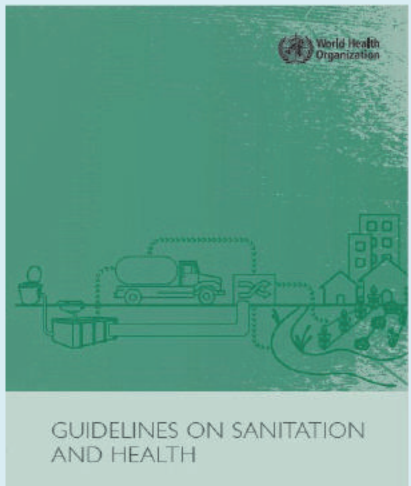

Figure 2.1.2 *Guidelines on sanitation and health.* World Health Organization (2018).

Example 2.1.2 Setting treatment objectives based on intended resource recovery

In the absence of regulations, a way to establish treatment objectives is to set them specifically for the intended resource recovery option. See chapter 1.2 for more details about the engineering design approach. The appropriate level of treatment will depend on the resource recovery or disposal option. For example, if faecal sludge is to be used as a fuel in combustion, the number one objective is dewatering to increase the fuel potential. In this case, lower levels of pathogen inactivation are acceptable (if protective measures for handling exist) as the faecal sludge will be incinerated. If faecal sludge is to be composted, and used for food crop production, pathogen reduction is the main goal. The treatment objective should always be linked with the enduse to ensure the protection of public and environmental health. This thinking also applies similarly to all of the four treatment objectives as well as the resource recovery options.

Exercises

1. Adequate sanitation services can help prevent the transmission of pathogens. By identifying the faecal-oral transmission pathways public health can be protected. Use the 'f' diagram above and explain the routes of contamination for each of the 'f' words.
2. Explain stabilization as a treatment objective. State whether stabilized or unstabilized faecal sludge is wanted for agricultural use and energy use, respectively.
3. Pathogen inactivation is important to protect public health. How does storage kill pathogens? (hint: pathogen inactivation mechanisms)
4. What would be different in your approach to nutrient management if the faecal sludge treatment effluent is used for irrigation or if it is disposed of into a surface water body?
5. Stabilization and nutrient management are interlinked. Describe why, and give two nutrients that are relevant to faecal sludge effluent.
6. When faecal sludge management is poorly managed it has a negative impact on the environment, and the public health. Link the potential negative impacts in the list below with the component of the faecal sludge that is responsible for the negative impact. Each bullet point can have more than one component.
   Faecal sludge components; pathogens, organic material, nutrient and water.
   - What makes people sick?
   - What component can increase algae in surface water and lead to the death of aquatic organisms?
   - What makes faecal sludge smell bad?
   - What makes faecal sludge heavy and voluminous to manage?
   - What component increases the risk of water contamination?
   - What component attracts rats and flies?
7. Why do treatment objectives ensure the protection of public and environmental health?
8. Explain how the treatment objectives as a concept contribute to the protection of public health, and to the protection of environmental health.
9. In the absence of regulations for the treatment of faecal sludge, working with the concepts of treatment objectives can be very beneficial. Explain why.
10. Assuming that the intended enduse for treated faecal sludge is to produce pellets to feed an electricity producing gasifier. Discuss the appropriate treatment objective(s).
11. Assuming that the intended enduse for treated faecal sludge is co-compost which will be applied on edible crops. Discuss the appropriate treatment objective(s).
12. Assuming that the intended enduse for treated faecal sludge includes the use of effluent for the irrigation of fruit trees. Discuss the appropriate treatment objective(s).
13. Discuss the importance of dewatering as a treatment objective during faecal sludge treatment.
14. You are the faecal sludge professional of a treatment plant. The water body outside the faecal sludge treatment plant indicates BOD levels over the regulatory limits. These have

led to depletion of oxygen in the surface water. What treatment objective(s) needs to be further enforced and/or evaluated in the faecal sludge treatment modification?

a) Dewatering
b) Stabilization
c) Nutrient management
d) Pathogen inactivation

15. Draw a line to link the events with the treatment objectives. The events can be linked to more than one treatment objective.

Events	**Treatment objectives**
Cholera outbreak	Dewatering
Increased diarrheal diseases	Stabilization
Fish die off in a lake	Nutrient management
Expensive transport of faecal sludge with high water content	Pathogen inactivation
High nitrate levels in faecal sludge effluent contaminate drinking water sources	

16. Assuming the intended enduse for treated faecal sludge is biochar as cooking fuel. Based on a multi-barrier approach, explain what barriers can be put in place to further protect public health.

Chapter 2.2

Overview of treatment mechanisms

Stanley Sam and Linda Strande

Learning objectives

- Know the difference between physical, chemical and biological treatment mechanisms
- Identify mechanisms for solid-liquid separation, stabilization, nutrient management, and pathogens
- Understand the mechanisms for key parameters that can be controlled to increase treatment efficiency and meet treatment objectives

Textbook

Available at www.sandec.ch/fsm_book

- Strande, L., Ronteltap, M. and Brdjanovic, D. (2014). *Faecal Sludge Management - Systems Approach for Implementation and Operation.*

Free online course (MOOC)

Available at www.eawag.ch/mooc

- *Introduction to Faecal Sludge Management.* MOOC series by Eawag and EPFL. Module ´Overview of Treatment Mechanisms´.

Further Eawag-Sandec publications

Available at www.sandec.ch/fsm_tools

- Gold, M., Dayer, P., Faye, M.C.A.S., Clair, G., Seck, A., Niang, S., Morgenroth, E. and Strande, L. (2016). *Locally produced natural conditioners for dewatering of faecal sludge.* Environmental Technology, 1-13.

Additional resources

- Kunz, A. and Mukhtar, S. (2016). *Hydrophobic membrane technology for ammonia extraction from wastewaters*. Eng. Agric., Vol. 36, No. 2.
- Mendez, J.M., Jiménez, B.E. and Barrios J.A. (2002). *Improved alkaline stabilization of municipal wastewater sludge.* Water Science and Technology, Vol. 46, No. 10, pp. 139-146.
- Metcalf & Eddy (2014). *Wastewater Engineering: Treatment and Resource Recovery.* 5th Edition, McGraw-Hill, New York.
- Spellman, F.R. (2014). *Mathematical manual for water and wastewater treatment plant operators*. Second edition, Taylor and Francis group.
- Vesilind, P.A. (1994). *The role of water in sludge dewatering*. Water Environment Research, Vol. 66, No. 1, pp. 4-11.

Introduction

Several technologies exist for the treatment of faecal sludge, and these technologies rely on physical, chemical or biological mechanisms in order to achieve their treatment objectives. In faecal sludge treatment, the efficiency of the employed treatment mechanism is affected by the variability in the characteristics of the faecal sludge. Some of the properties of the faecal sludge that must be considered include water content, pH, dissolved oxygen, degradable organic matter, nutrients, density, particle size and pathogens. Fundamental mechanisms for the treatment of faecal sludge are not yet as well understood as in wastewater treatment. This is the reason why there is a need to understand these mechanisms in order to help to improve the design and operation of faecal sludge treatment technologies.

Dewatering

One of the greatest challenges in faecal sludge treatment is dewatering. Since water makes up over 90% of faecal sludge mass, it increases the cost of transport and hinders resource recovery (Gold *et al.,* 2016). Dewatering is based on physical processes such as evaporation, evapotranspiration, filtration, gravity, surface charge attractions, centrifugal force and pressure. Drying of faecal sludge is a process that results in the evaporation of water from the sludge or filtration through the drying media. Gravity is probably the most commonly employed method of solid-liquid separation for the separation of suspended particles and unbound water. The process can be aided by the addition of coagulants such as alum, lime, ferric chloride and organic polymers to destabilize colloidal particles and cause bridging of the particles into larger flocs, which enhances sedimentation and ultimately improves dewatering (chapter 5.2). The rate of dewatering depends on the distribution of water in the sludge. The bound water is much more difficult to remove than free water.

Stabilization and nutrient management

The organic matter in faecal sludge is highly variable and requires stabilization before disposal or enduse. Stabilization involves the reduction of organic matter. It also reduces the water content, pathogens and unpleasant odours. Stabilization can occur under aerobic and anaerobic conditions, and can take place in many different technologies including stabilization ponds, planted drying beds and co-composting. Through metabolism, complex organic compounds are broken down into simpler forms and utilised by microorganisms for growth. During the growth of these microorganisms, inorganic nitrogen and phosphorus are immobilised into cells. As the organic matter is degraded in biological treatment processes, the bound phosphorus and nitrogen are mineralised and released.

Pathogens

Protection of public health is the number one goal of faecal sludge management, and so it is important to have an understanding of all of the interrelated ways to reduce pathogens during treatment. The main mechanisms of pathogen inactivation are: predation from other organisms, starvation, temperature, UV penetration, pH, time, desiccation or dehydration, and sorption. They can also affect the performance of treatment technologies.

Example 2.2.1 Different mechanisms in treatment processes

For more information and examples refer to the MOOC series *Introduction to Faecal Sludge Management* and the book *Faecal Sludge Management - Systems Approach for Implementation and Operation.*

Unplanted drying beds – physical mechanism

In unplanted drying beds, the separation of solids and liquids occurs through physical mechanisms. The water in the sludge percolates through the sand and gravel filter media layers of the bed and the solids content stays on top of the bed. Further removal of water occurs by drying which involves the evaporation of water from the sludge into the atmosphere. The dried sludge can be further treated for pathogen inactivation and stabilization. Refer to chapter 3.3 for more information about unplanted drying beds.

Anaerobic digestion – biological mechanism

Anaerobic digestion occurs in oxygen-deficient environments and is used in the stabilization of faecal sludge. The process makes use of different microorganisms existing in a balanced relationship to convert complex organic waste into biogas. In addition to waste stabilization, methane generation has the additional benefit of offsetting energy utility expenses. Anaerobic digestion occurs in digesters, septic tanks, waste stabilization ponds and settling tanks. The microbial degradation of organic matter is a biological mechanism that produces a stabilised organic material, which is resistant to further biodegradation. Refer to chapter 5.1 for more information about anaerobic digestion.

Alkaline stabilization – chemical mechanism

The addition of alkaline chemicals to faecal sludge aims at stabilizing the sludge, reducing pathogen levels, and improving flocculation and settling properties of the sludge. Lime and quicklime are examples of alkaline chemicals used for the stabilization of faecal sludge. The addition of adequate quantities of lime results in an increase in pH to 12 and stops microbial activity. However, the pH elevation resulting from the addition of lime not only reduces microorganisms, but also causes the conversion of NH_4^+ into ammonia gas (NH_3). Ammonia also acts as a disinfectant, significantly reducing bacteria populations and Helminth eggs or ova. Figure 2.2.1 is a graphical representation of the conversion of NH_4^+ into NH_3 with respect to changes in the pH of a system. Refer to chapter 5.5 for more information on lime stabilization.

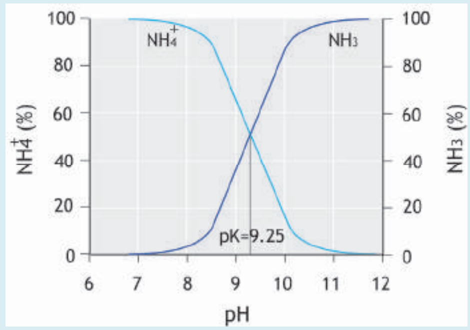

Figure 2.2.1 Ammonium and ammonia distribution as a function of pH (Kunz *et al.,* 2016).

Exercises

1. For the protection of public health, pathogen inactivation is crucial. Briefly describe three physical mechanisms for pathogen inactivation. Explain each with one sentence and include a treatment technology where relevant.
2. Unplanted and planted drying beds are two established faecal sludge treatment technologies. What are the treatment objectives for both of these technologies? Specify the treatment mechanism for each of these treatment objectives.
3. Filtration and drying are physical processes of dewatering used in faecal sludge management.
   a) What is the difference between them?
   b) Name one treatment technology that uses both filtration and drying as dewatering processes.
4. Stabilization of faecal sludge can occur through biological and chemical mechanisms. Give a treatment technology example for each of these stabilization processes that use biological and chemical mechanisms.
5. The end product of a faecal sludge treatment plant in a city is to be used as biofuel. The thermal drying process is used to remove excess water in the dewatered sludge. The end product of the treatment process is found to contain very low level of pathogens. What is the possible mechanism that resulted in pathogen inactivation? Indicate whether it is a physical, biological or chemical mechanism.
6. Evaporation and transpiration are physical mechanisms that are involved in the dewatering of faecal sludge. Differentiate between the two processes, indicate in which treatment process they are involved and state four factors that affect evaporation.

7. For the following treatment processes, indicate whether the mechanisms involved are physical, chemical or biological.
   - Pathogen inactivation by composting
   - Stabilization by anaerobic digestion
   - Dewatering by addition of organic polymers
   - Stabilization by composting
   - Dewatering by centrifugation
   - Pathogen inactivation by ammonia addition
8. Thermal drying is a physical mechanism used to further remove water from dewatered sludge. Give two factors that influence the rate of drying of the sludge.
9. Briefly explain mineralisation, and specify whether it is a physical, chemical or biological mechanism.
10. Ammonia treatment, which is a chemical process of pathogen inactivation, is dependent on the pH of the sludge. Explain how pH affects the process of pathogen inactivation by ammonia.
11. In a pit latrine that has been abandoned for two years, the number of Helminth eggs is found to be three orders of magnitude lower than that of a similar septic tank that is emptied every six months. Give a possible explanation why.
12. At a treatment plant in Ghana, two drying beds are used for drying faecal sludge that is discharged from two different sources. The first drying bed is loaded with faecal sludge with a TSS concentration of 1,200 mg/L and the second with faecal sludge with a TSS of 550 mg/L. Determine which one of the drying beds will have a higher filtration rate, and why?
13. Filtration is used in unplanted drying beds for separating the solids and liquids in faecal sludge. During filtration, solids are trapped on the surface of the filter. Operation can lead to clogging and reduction in filtration efficiency.
    a) As the senior engineer at the treatment plant, explain how clogging can be prevented.
    b) What are the critical parameters that have the greatest effect on the filtration efficiency?
14. As a plant supervisor, you have the option of choosing between two different dewatering technologies, one that uses centrifugation and another that uses thermal drying.
    a) What will influence your choice of technology?
    b) Based on your selection, state the advantages of the selected mechanism and the limitation of the other mechanism not selected.
15. During your field visit in Senegal, you observed that the inhabitants periodically add quicklime to their pit latrines with the idea that it reduces the odour in the toilet. As an engineer, explain the mechanism and function of the quicklime.

Chapter 2.3

Resource recovery

Miriam Englund and Linda Strande

Learning objectives

- List different forms of resource recovery from treatment products
- Identify ways in which treatment products can be used
- Name characteristics that are important for different resource recovery products

Textbook

Available at www.sandec.ch/fsm_book

- Strande, L., Ronteltap, M. and Brdjanovic, D. (2014). *Faecal Sludge Management - Systems Approach for Implementation and Operation.*

Free online course (MOOC)

Available at www.eawag.ch/mooc

- *Introduction to Faecal Sludge Management.* MOOC series by Eawag and EPFL. Module 'Resource recovery'.

Further Eawag-Sandec publications

Available at www.sandec.ch/fsm_tools

- Andriessen, N., Ward, B.J. and Strande, L. (2019) *To char or not to char? Review of technologies to produce solid fuels for resource recovery from faecal sludge.* Journal of Water, Sanitation and Hygiene for Development.
- Diener, S., Semiyaga, S., Niwagaba, C.B., Muspratt, A.M., Gning, J.B., Mbéguéré, M., Ennin, J.E., Zurbrügg, C. and Strande, L. (2014). *A value proposition: Resource recovery from faecal sludge - Can it be the driver for improved sanitation?* Resources, Conservation and Recycling, 88, 32-38. doi:10.1016/j.resconrec.2014.04.005
- Gold, M., Cunningham, M., Bleuler, M., Arnheiter, R., Schönborn, A., Niwagaba, C. and Strande, L. (2018). *Operating parameters for three resource recovery options from slow-pyrolysis of faecal sludge.* Journal of Water, Sanitation and Hygiene for Development 8 (4): 707-717.
- Tilley, E., Ulrich, L., Lüthi, C., Reymond, P. and Zurbrügg, C. (2014). *Compendium of Sanitation Systems and Technologies.* 2nd edition. Dübendorf, Switzerland, Swiss Federal Institute of Aquatic Science and Technology (Eawag). www.sandec.ch/compendium

- Ward, B.J., Gold, M., Turyasiima, D., Studer, F., Getkate, W., Maiteki, J.M., Niwagaba, C.B. and Strande, L. (2017). *SEEK (Sludge to Energy Enterprises in Kampala): Co-processing Faecal Sludge for Fuel Production*. 40th WEDC International 722 Conference, Loughborough, UK.

Additional resources

- Metcalf & Eddy (2014). *Wastewater Engineering: Treatment and Resource Recovery.* 5th edition, McGraw-Hill, New York.
- IWMI Publications on Resource Recovery & Reuse Series. Available at http://www.iwmi.cgiar.org/publications/resource-recovery-reuse/

Introduction

Ideally, faecal sludge should be seen as a resource that can be recovered, rather than a waste that needs to be managed and disposed of. With adequate collection and treatment, faecal sludge can be transformed into treatment products that can be sold and utilized. For example, the water, organic matter, and nutrients in faecal sludge can be beneficial for soil properties and plant growth. The organic matter is beneficial for water retention, which can increase water-holding capacity and reduce the effects of drought, reduce soil erosion, and benefit the soil microbial community.

It is important to consider the protection of public health, as well as public perception, with the use of treatment products. For safe resource recovery by endusers, it is important that pathogen levels are adequately controlled for the intended enduse, for example commercially available compost versus industrial fuel. Similarly, considering social acceptance of the product by the intended market is critical, for example selling faecal sludge briquettes to individuals as a household cooking fuel, as opposed to industrial customers.

Treatment product

Resource recovery can be from both the solid and liquid fractions of faecal sludge. The types of treatment products will depend on the initial characteristics and on the treatment technologies. Examples of established forms of resource recovery include dewatered or dried sludge produced from unplanted drying beds for land application; co-composting of faecal sludge and organic solid waste (see chapter 3.5); plants from planted drying beds (see chapter 3.4); deep-row entrenchment of untreated faecal sludge; or effluent from waste stabilization ponds used for irrigation or in aquaculture. Transferring and innovative treatment products include biogas from the anaerobic digestion of faecal sludge (see chapter 5.1), larvae from the treatment with black soldier fly (see chapter 5.4), and carbonization of faecal sludge (see chapter 5.3).

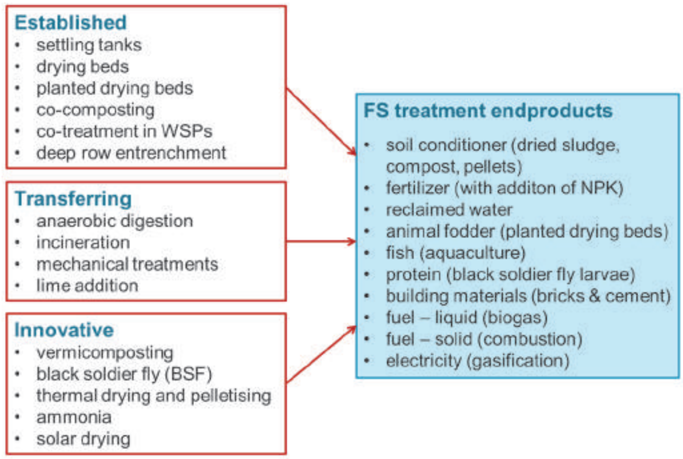

Figure 2.3.1 **Level of establishment of faecal sludge treatment technologies and their treatment endproducts (taken from the MOOC '*Introduction to Faecal Sludge Management*').**

Application

Another way to think about resource recovery is by the actual resource that it provides, which is especially useful when thinking about the potential market demand. For more information on the market-driven approach (MDA), see chapter 2.4. Treatment products can also be further processed to increase their market value. For example, further processing of char into briquettes that are suitable for recovery of its energy in institutions, or pelletizing of compost or dewatered (dried) sludge for easier transport.

Table 2.3.1 **Summary of the potential resources and the treatment products (Taken from: Schoebitz, L., Andriessen, N., Bollier, S., Bassan, M. and Strande. L. (2016). *Market Driven Approach for Selection of Faecal Sludge Treatment Products*).**

Resource	Treatment product	Product type
Energy	Solid fuel	Pellets, briquettes, powder
Energy	Gas fuel	Biogas
Energy	Electricity	Conversion of biogas, or gasification of solid fuel
Food	Protein	Black soldier flies, fish meal
Food	Animal fodder	Plants from drying beds, dried aquaculture plants
Food	Fish	Grown on effluent from faecal sludge treatment
Material	Building materials	Additive to bricks, road construction
Nutrients	Soil conditioner[1]	Compost, pellets, digestate, black soldier fly residual
Nutrients	Fertilizer[2]	Pellets, powder
Nutrients	Soil conditioner[3]	Untreated sludge, dewatered sludge from drying beds
Water, nutrients	Reclaimed water	Effluent from faecal sludge treatment

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[1] With different levels of pathogen removal, based on enduse
[2] Addition of NPK to fulfill nutrient needs of a fertilizer
[3] No pathogen removal.

Suitable faecal sludge characteristics for treatment products

Different characteristics of faecal sludge will affect the quality of the treatment endproduct, and will need to be evaluated to ensure that they meet market needs, and also to protect public and environmental health. As explained in chapter 2.1 Treatment objectives, it is challenging to ensure that faecal sludge is completely pathogen-free. Therefore, the multi-barrier approach (see *Guidelines on sanitation and health.* WHO, 2018) can be used to protect public and environmental health when using faecal sludge as a treatment product. Relevant characteristics to consider include the following:

Land application

- Nutrients such as nitrogen, phosphorus and potassium are essential for plant growth and important for the use of effluent for irrigation, and as a soil conditioner, compost or fertilizer.
- Heavy metals, such as cadmium, lead and zinc, and salinity are important as they can be toxic to plants and people.
- Indicators of pathogens for both liquid and solid streams to ensure that resource recovery adequately protects public health.

Solid fuels

- The calorific value is a measure of the energy content of a fuel, and is important for the characterization of solid fuel.
- Ash content is a metric of the non-combustible, inorganic fraction contained in faecal sludge, and it does not contribute to the calorific value. It needs to be disposed of, or used for phosphorus recovery.
- Indicators of pathogens are important depending on the final enduse, and risks need to be managed with a multi-barrier approach (see chapter 2.1 *Treatment Objectives* for more information).

Biogas

- Fractions of methane and carbon dioxide are important parameters for biogas, as higher methane and lower carbon dioxide concentrations increase the fuel potential.

Animal feed

- The protein, fat and mineral contents are important for the use of insect larvae and plants as animal feed.
- Indicators of pathogens are important to ensure that pathogens are not transmitted to animals.

Case study 2.3.1 Resource recovery in Lubhu (Nepal)

This case study is provided by ENPHO.

The Lubhu faecal sludge treatment plant is located 7 km east of Kathmandu, Nepal, and is designed to receive 6 m^3 faecal sludge per week. Lubhu provides an example of how a decentralized faecal sludge treatment plant can be integrated into a community in a safe and useful way through resource recovery of the endproducts. The treatment process flow as designed by ENPHO is presented in Figure 2.3.2.

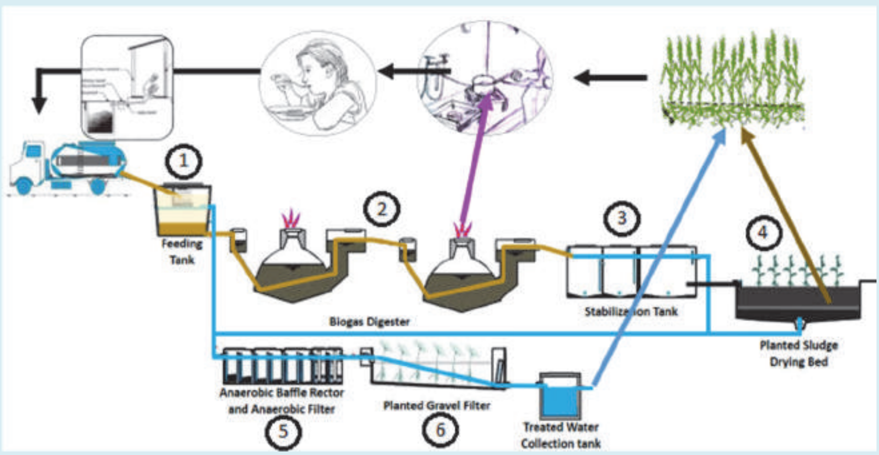


Figure 2.3.2 Process flow diagram of the Lubhu faecal sludge treatment plant, provided by ENPHO.

The operational and maintenance plan also provides an incentive for the caretaker of the treatment plant to maintain it well, as they are a direct beneficiary of the resource recovery treatment products. The caretaker was previously by profession a farmer, and was given additional training in safe enduse of treated effluent and dewatered sludge based on the *Sanitation safety planning manual for safe use and disposal of wastewater, greywater and excreta* by WHO, 2015.

Resource recovery

- Biogas as cooking fuel. The anaerobic digesters produce biogas that is captured and fuels a household cooking stove for the caretaker. The gas production is not optimized but produces enough gas to daily fuel a stove for a five-member family.
- Treated effluent for irrigation. Effluent from the gravel filter is used for irrigation, for crops that do not come into direct contact with the water, for example the orange trees shown in Figure 2.3.3.
- Dewatered sludge as a soil amendment. Sludge from the planted drying beds is used as a soil amendment, also for crops that do not come into direct contact with the sludge.

Figure 2.3.3 An orange tree grown with faecal sludge in Lubhu, Nepal.

Case study 2.3.2 Resource recovery in Faridpur (Bangladesh)

This case study is provided by Practical Action.

In Bangladesh co-composting of faecal sludge with other organic waste is becoming more common for faecal sludge treatment, meaning in the future, there will more information on co-composting for the design and operation of treatment plants. The Faridpur faecal sludge treatment plant, also called the Compost Research and Training Center (CRTC), is located in Faridpur in Khulna Division, Bangladesh, and is designed to receive 24 m^3 faecal sludge per day.

The treatment plant is comprised of the following stages: (1) two modules of eight unplanted sludge drying beds (UDB); (2) two modules of six planted drying beds (PDB); (3) one dewatered (dried) sludge storage area; (4) six anaerobic baffled tanks; (5) six horizontal-flow constructed wetlands (HFCW) in series; and (6) one maturation pond. The layout of the treatment plant is presented in Figure 2.3.4.

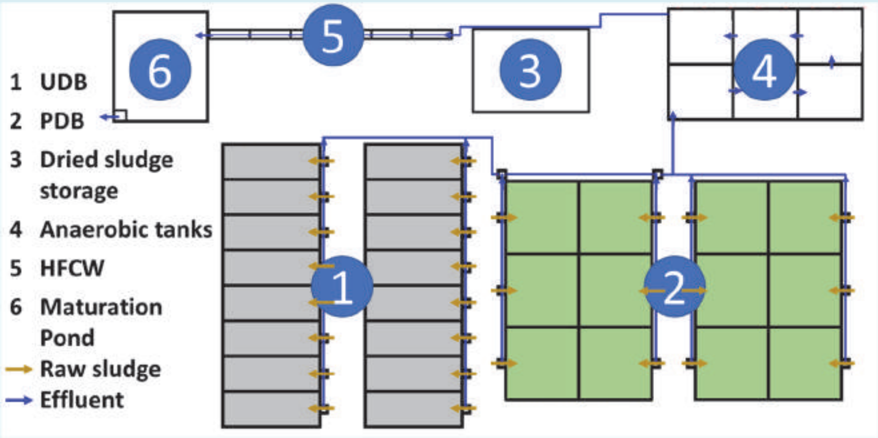


Figure 2.3.4 Faecal sludge treatment plant layout and flow diagram.

Figure 2.3.5 Preparation of the dewatered sludge cakes in Faridpur, Bangladesh, prior to transportation to the nearby co-composting plant.

CRTC has compared what is most beneficial in terms of resource recovery, and is currently operating the unplanted drying beds and selling the dewatered faecal sludge to a near-by co-composting plant. The faecal sludge treatment plant is currently under capacity. In the future, as the loadings increase, the planted drying beds will also be used, as they require a smaller footprint for increased loadings of faecal sludge. Revenue from the sale of dewatered sludge offsets operation and maintenance costs, and in the future this can also include harvested plants from the planted drying beds.

The steps to prepare the dewatered sludge to be sent to the co-composting plant are:

- Dewatered sludge is manually removed from the drying beds and stored in a shed.
- In the shed the dewatered sludge is broken down into smaller pieces.
- The sludge is then sieved to remove any inorganic wastes.
- The sieved sludge is packed into bags which are sold and transported to the co-composting plant a few kilometres away.

Practical Action emphasises that continuous monitoring of the co-composting product is important. They plan to establish an onsite laboratory to make sure that the final endproduct has adequate pathogen removal. Their number one goal is always protection of public health.

Exercises

1. a) What resource recovery treatment product is depicted in Figure 2.3.6?

Figure 2.3.6 Faecal sludge treatment plant in Dakar, Senegal.

b) What resource is provided by this treatment product?
c) What product type(s) can be provided by this treatment product?
d) How is this product used?

2. Explain how the products of the following treatments can be used and give one example for each:
   a) Planted drying beds
   b) Unplanted drying beds
   c) Waste stabilization ponds
3. You are the operator of a small-scale faecal sludge treatment plant that is selling the dewatered solids and the treated effluent from a gravel bed to a nearby farmer. What type of monitoring plan do you need to ensure the protection of human and environmental health? What parameters would you measure?
4. What could be a benefit of making pellets with dewatered sludge, compared to selling the dewatered sludge as it is? What are the potential negative aspects?
5. Explain why brick factories might be interested in the dewatered solids from unplanted drying beds.
6. a) What resource recovery treatment product(s) is depicted in Figure 2.3.7?

Figure 2.3.7 Faecal sludge treatment plant in Jhenaidah, Bangladesh.

b) What resource is provided by this treatment product?
c) What product type(s) can be provided by this treatment product?
d) How is this product used?

7. Treatment technologies can deliver a treatment product that can be recovered as a resource. Complete the following sentences; multiple correct combinations of answers are possible.

a) Black soldier flies are a(n) ____________ treatment technology for faecal sludge and produce ____________ that can be used as animal fodder.
b) ________________________ is/are an established treatment technology and produce dewatered (dried) sludge as a treatment endproduct that can be used for ________________________.
c) The effluent from a waste stabilization pond can be used for ____________ purposes or in ______________.
d) ____________ produced from faecal sludge can be directly used in cooking stoves, or converted into ____________.
e) ____________ can come in many forms, for example powder and ____________; the important resource is the ____________.

8. The use of dewatered faecal sludge in land applications is common in many countries.
   a) What important factors should be considered before using faecal sludge for land applications?
   b) Discuss different levels of pathogen reduction for agriculture depending on the type of crop: 1) food crops that do not come into contact with the sludge and are peeled prior to eating, and 2) direct application to edible crops.

9. Even if it is technically possible to transform faecal sludge into a treatment product there are several other factors that need to be considered. Apart from the appropriate treatment technology to generate a product, what else do you need to consider?

10. The municipality of a densely populated city with 200,000 inhabitants has decided to invest in a faecal sludge treatment plant, and hopes to incorporate resource recovery. There is a large banana plantation next to the proposed site, which are sold in the capital city 15 km away. The main source of water for irrigation is a nearby lake that also supports a local fish market.
    a) Suggest resource recovery options for use.
    b) What considerations should be evaluated prior to the selection of a resource recovery option?

11. Use the columns below to link together the correct resource with its application(s) and also with the important faecal sludge characteristics.

Resource	Application	Important faecal sludge characteristics
		Ash
		Cadmium
		Calorific value
		Carbon dioxide
	Biogas	E-coli
Energy	Briquettes	Fat
Food	Fertilizer	Helminth eggs
Nutrient	Insect larvae as animal feed	Lead
Water	Irrigation	Methane
	Pellets	Minerals
	Soil amendment	Nitrogen
		Phosphorus
		Potassium
		Protein
		Salinity

Chapter 2.4

The Market-Driven Approach to selecting treatment products

Nienke Andriessen and Linda Strande

Learning objectives

- Explain how a Market-Driven Approach is implemented
- Understand how this tool fits within an integrated engineering design approach

Textbook

Available at www.sandec.ch/fsm_book

- Strande, L., Ronteltap, M. and Brdjanovic, D. (2014). *Faecal Sludge Management - Systems Approach for Implementation and Operation.*

Free online course (MOOC)

Available at www.eawag.ch/mooc

- *Introduction to Faecal Sludge Management.* MOOC series by Eawag and EPFL. Module ´Market-driven approach to select treatment products´.

Further Eawag-Sandec publications

Available at www.sandec.ch/fsm_tools

- Andriessen, N., Schoebitz, L., Bollier, S., Bassan M. and Strande, L. (2017). *Market Driven Approach for faecal sludge treatment products.* 40th International WEDC Conference, Loughborough, UK.
- Market-Driven Approach data collection tool: www.sandec.ch/mda
- Schoebitz, L., Andriessen, N., Bollier, S., Bassan, M. and Strande. L. (2016). *Market Driven Approach for Selection of Faecal Sludge Treatment Products.*
- Strande, L. Gold, M., Schoebitz, L. and Bassan, M. (2016). *Engineering Approach for Selection and Design of Treatment Technologies.* Sandec News 17.

Introduction

When following the engineering design approach (chapter 1.2) for faecal sludge management, first of all treatment objectives need to be defined. There are often no existing standards for faecal sludge treatment products, which makes it challenging to define performance goals.

One way to do this is to think from a resource recovery perspective, and first determine what faecal sludge treatment products are desired, and then choose treatment objectives and performance goals to meet the required treatment level. For example, when applied as a fertilizer on edible crops, pathogen removal is an extremely important treatment objective, but when burning it as a solid fuel, complete pathogen removal has less focus. Based on the desired treatment product, a performance standard can then be chosen.

In the absence of clear legal frameworks for faecal sludge treatment products, identifying those which are most attractive to the market provides a method to help select the most suitable treatment products. In addition to the greatest potential for generating revenue, this can also help to ensure the design of adequate treatment and to promote sustainable operation as plant managers have to meet customer demand.

The Market-Driven Approach (MDA) is a quantitative method developed by Sandec to evaluate the market for potential products resulting from the treatment of faecal sludge. The manual and calculation tool can be downloaded from the Sandec website www.sandec.ch/mda (Schoebitz *et al.*, 2016).

As illustrated in Figure 2.4.1, the market attractiveness in the MDA takes into account both the current market volume and the future potential market growth.

Figure 2.4.1 Market attractiveness comprises of market volume and market growth (Schoebitz *et al.* 2016).

Market volume is defined as the sum of the value of all the available products in a given market. For example, for animal feed that would be the price and number of units sold in a defined geographical area. Market growth is defined as the growth of the type of product over a specified period (e.g. 5 years, but can also be shorter or longer, depending on what information is available). As this cannot yet be determined, the historical growth of a product can be extrapolated to estimate future growth. A market attractiveness graph is then created by plotting market growth with market volume; see step 6 in Example 2.4.1.

The input data is collected through a literature review, as well as interviews to crosscheck the values obtained from the literature and to supplement any missing information.

Step-by-step approach for the Market-Driven Approach

Examples in the following step-by-step approach, see Table 2.4.1, are summarized from Andriessen *et al.* (2017). For this exercise book, some steps have been slightly simplified. The full step-by-step methodology is explained in Schoebitz *et al.* (2016).

Table 2.4.1 Steps included in the Market-Driven Approach. Source: Andriessen *et al.* (2017).

Step 1	Review list of potential faecal sludge treatment products
Step 2	Identify potential product application
Step 3	Define products that are used
Step 4	Calculate market volume
Step 5	Assess market growth
Step 6	Combine market volume and market growth
Step 7	Compare products

Step 1: Review list of potential faecal sludge treatment products

Define the type(s) of resource recovery that are relevant to the city (e.g. energy, nutrients, feed), and then select the relevant treatment products. Table 2.4.2 presents a list of possible treatment products from Schoebitz *et al.* (2016).

Table 2.4.2 Potential faecal sludge treatment products (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 soldier flies, fish meal
Food	Animal fodder	Plants from drying beds, dried aquaculture plants
Food	Fish	Grown on effluent from faecal sludge treatment
Material	Building materials	Additive to bricks, road construction
Nutrients	Soil conditioner[1]	Compost, pellets, digestate, black soldier fly residual
Nutrients	Fertilizer[2]	Pellets, powder
Nutrients	Soil conditioner[3]	Untreated sludge, dewatered sludge from drying beds
Water, Nutrients	Reclaimed water	Effluent from faecal sludge treatment

[1] With different levels of pathogen removal, based on enduse

[2] Addition of NPK to fulfill nutrient needs of a fertilizer

[3] No pathogen removal

Step 2: Identify potential product application

Find information about where these products can be used. For example, in which industry? Or are they used on a household level? Then list each application. For example, in Kampala, the product solid fuel is used for cooking in households and is also used as fuel in brick factories.

Step 3: Define products that are used

Because a market for faecal sludge treatment products frequently does not yet exist, market volume cannot be directly identified. Therefore, start by determining market volume by looking at what products are currently used that could be replaced with faecal sludge products. These are called substitute products. So, for example, charcoal, firewood and coffee husks are currently used as solid fuel in Kampala. These are substitute products that could be replaced by dried faecal sludge.

Step 4: Calculate market volume

Calculate the current market volume for each substitute product, through literature reviews and conducting interviews. To calculate the market volume, you could use the average price per product multiplied by the number of products sold in a city. Alternatively, the average price per product multiplied by the number of products sold by suppliers, multiplied by the number of suppliers in the city, could be used. In Kampala, the market volume for charcoal was found to be approximately 73 million. This is typically not an exact number, but this method gives a reasonable preliminary estimation and then further crosschecking is carried out in order to make it as accurate as possible.

Step 5: Assess market growth

Assess the market growth for each substitute product. In some cases, trend forecasts are available. Others can be estimated by extrapolation from previous years together with interviews to crosscheck. At the time of our implementation the estimated market growth of charcoal in Kampala was 9%, over a period of five years.

Step 6: Combine market volume and market growth

Compare the market volume and the market growth for each product. By combining market volume and market growth, it is possible to make a judgement as to which product has the highest market potential or market attractiveness. Each substitute product identified in step 3 is plotted here. The higher the combined market growth and market volume, the greater the market attractiveness is (Figure 2.4.2).

Step 7: Compare products

After the market attractiveness of faecal sludge treatment products has been established, how can that information be used? It is important to note that comparing the market attractiveness of various faecal sludge treatment products is relative and subjective. In the end, the professional carrying out the method is the one who decides which treatment product is most suitable in the local context. This information cannot be used in isolation. It needs to be incorporated into a comprehensive design approach for selection of treatment technologies to help make intelligent design decisions. The number one goal must always be the protection of public health. The MDA, as a financial perspective on resource recovery, is just one tool in the whole process. Consider it with other factors, such as local laws and regulations, availability of financial resources, human capacity, land area available for treatment technologies, and the faecal sludge quantities and qualities that will be coming into treatment facilities, and then make a final decision on what product is most appropriate.

Case study 2.4.1 Implementing the MDA in Ba Ria, Vietnam

This example is based on the results from field-testing the methodology in Ba Ria, Vietnam. Ba Ria is a provincial, peri-urban city with a population of 69,293 in the South of Vietnam. An analysis of the field-test results can be found in Andriessen *et al*. (2017).

Step 1: Review list of potential faecal sludge treatment products
All treatment products in Table 2.4.2 were evaluated for their relevance in Ba Ria. Three different types of treatment products were selected as relevant: fertilizer, protein (from black soldier flies) for animal feed, and solid fuel.

Step 2: Identify potential product application
For each treatment product, it was defined where or by whom that type of product is used. Fertilizer is currently used by plantation farmers (e.g. tobacco, coffee, cashew), and in the horticulture sector. Animal feed can be used by livestock farmers, and also in aquaculture (prawn farms) which is present in the area. Solid fuels are used by households for cooking, and by brick producers.

Step 3: Define products that are used
For each product application, the products that are currently used were listed. These are the substitute products. As a fertilizer, organic fertilizers (compost) and chemical fertilizers are currently used. For protein in animal feed, commercial poultry feed is used in the poultry sector, and commercial pig feed is used in the pig farming sector. The protein fraction in these feeds could potentially be replaced by the faecal sludge treatment product protein from black soldier fly larvae. The substitute product that is currently used in aquaculture is worms. Solid fuel products that are currently used by households for cooking are charcoal briquettes. There is one wholesaler in the city that sells the charcoal briquettes to households. Brick producers use coal that they buy directly from the producer as their solid fuel source.

Step 4: Calculate market volume
The market volume for each substitute product was calculated in one of two ways: 1) by obtaining the market volume of the substitute product directly from the supplier or from the Department for Agriculture and Rural Development, or 2) by determining the number of product units sold within the city, and multiplying that number by the average price per unit.

The Department for Agriculture and Rural Development keeps track of fertilizer sales in the region. Organic fertilizers are the most popular in Ba Ria. Their market volume was estimated to be 154 million US$. The market as it is now has the potential to quickly incorporate a faecal sludge product. Chemical fertilizers (NPK) occupy a smaller portion of the market because of their price. The total estimated market volume for chemical fertilizers is 36 million US$.

There are 242 agencies that supply commercial poultry and pig feed to the farmers. The Department for Agriculture and Rural Development estimates that the market volume for pig feed is 6.5 million US$, and 1 million US$ for poultry feed. A fraction of the suppliers were interviewed to crosscheck this number. Aquaculture farms were interviewed for their feed demands. The market volume was estimated at 3.5 million US$. Aquaculture farmers showed a positive attitude towards using black soldier fly larvae in their farms. In total, the market volume for protein from black soldier fly larvae for livestock feed and aquaculture is estimated to be 11 million US$.

There is one charcoal briquette supplier in Ba Ria and five brick producers. The briquette supplier sells approximately 300 units of briquettes per day at 0.25 US$/unit. Through interviews the total coal consumption for the brick factories was calculated as approximately 3 million US$/year.

Step 5: Assess market growth
Market growth is determined by using existing forecasts, or by extrapolating growth rates from previous years (whichever is available). In Ba Ria, the Department for Agriculture and Rural Development has a good overview of the economic activity, and also provides forecasts for market growth for many of the substitute product sectors.

The market growth for fertilizers is difficult to predict, as there are many small farmers and regulations change regularly which affects the demand and growth of the sector. Overall, it was estimated that demand will decrease because of regulations.

The number of large-scale poultry, pig and aquaculture farms has been growing in the city in recent years. The Department for Agriculture and Rural Development forecasts that this industry will continue to increase until at least 2020, at a growth rate of 4%.

Market growth for charcoal briquettes could not be estimated. The master plan on construction materials in Ba Ria province estimates a large increase in brick production in the coming decade (2020-2030), corresponding to a market growth of 45%.

Step 6: Combine market volume and market growth
The results from market volume and market growth were combined and plotted in a graph with market growth on the X-axis and market volume on the Y-axis.

	Market volume (US$/year)	Market growth (%)
Fertilizer	190 million	- 10% (decrease)
Animal feed	11 million	4%
Solid fuel	3 million	45%

The resulting graph looks like this:

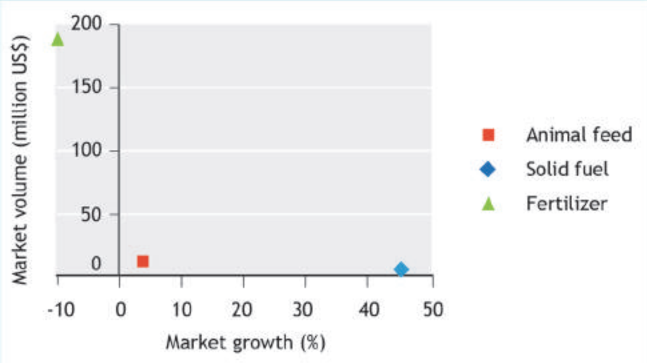


Figure 2.4.2 Market volume and market growth plotted to evaluate market attractiveness.

Step 7: Compare products

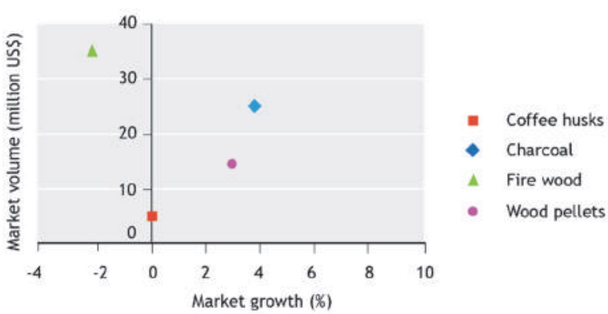
Researching the information in this case study has helped us to understand the situation in Ba Ria, and it can also help to interpret the graph. The interviews with the various stakeholders in the market also provided information on their attitude towards using faecal sludge products, and on the actual situation 'on the ground'. The market volume of fertilizers accounts for more than 90% of the total estimated market volume in Ba Ria. Chemical fertilizers are also encouraged by the local authorities. Even with an estimated shrinkage in the market growth, fertilizers are a safe option for resource recovery from faecal sludge treatment products in Ba Ria. Nevertheless, both animal feed and solid fuel for brick production also have potential if the treatment product can meet the user demands.

This information is only one part of deciding on relevant resource recovery options. It only provides input on the financial/market demand side. Factors such as local infrastructure, laws and regulations, social preferences, and technical capacity must also be considered when deciding on a final resource recovery strategy.

Exercises

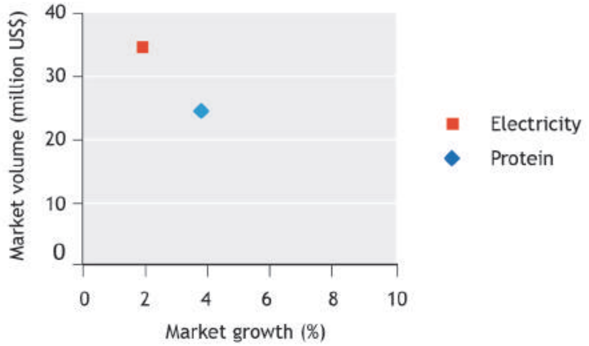
1. Why would someone use the MDA?
2. What is the definition of treatment products?
3. What is the number one goal of resource recovery from faecal sludge?
4. Market growth is difficult to predict; give one example on how it can be determined.

5. The MDA is only one tool in a whole process when designing treatment options for faecal sludge. Many factors need to be considered together with the MDA tool. Name three other factors that should be considered when deciding on faecal sludge treatment options.
6. The product of market volume and market growth gives the market attractiveness; what is the definition of market volume?
7. Under which treatment product category do protein, and plants from planted drying beds fall?
   a) Material
   b) Nutrients
   c) Food
8. Which treatment products belong to the resource recovery category 'Energy'? Choose one of the following four answers.
   a) Biogas, animal fodder and black soldier fly larvae
   b) Solid fuels, electricity and soil conditioner
   c) Electricity and building materials
   d) Electricity, biogas and solid fuels
9. Practice with step 2: 'Identify potential product application'. Name three different types of users that could use the treatment product protein from black soldier flies.
10. You are searching for data on the market volume of the substitute product compost. Therefore, you are looking for the number of compost suppliers in your city. Where would you look for this information?
11. This is the market attractiveness plot for all substitute products of the faecal sludge treatment product solid fuel in one city. How would you evaluate this plot? Write something about each substitute product.

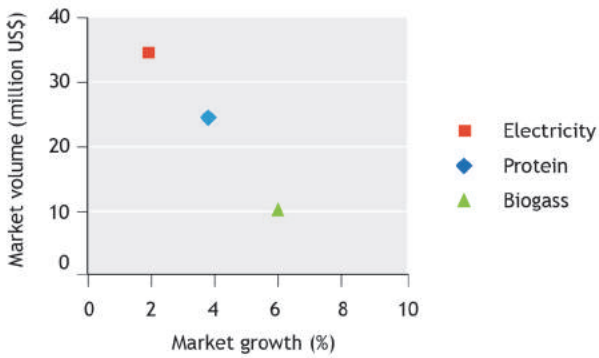


12. The market attractiveness plot can also be simplified to show several treatment products combined in one plot. In a city in South Asia, electricity has a high market volume and a high market growth. Protein for animal fodder has a smaller market volume, but also a reasonable market growth, though not as high as electricity, see graph below. The state is the only electricity provider in the city, but it has extremely lengthy procedures to get a licence to feed electricity produced from faecal sludge back to the grid. Based on the

provided information, would you choose electricity or protein as the most suitable treatment product? Explain your answer.



13. Betty and Sophie are discussing the market attractiveness plot below.



Betty says: "I would select electricity as the most attractive treatment product, because the market volume is very high, and there is still a 2% growth in the market."
Sophie says: "I would select biogas. Although the market volume is not very large, the market growth is high and it is therefore expected that in the coming years the market could yield more revenue."
Who do you agree with and why?

14. The hypothetical city of Delfinia is planning to build a faecal sludge treatment plant. They want to determine treatment objectives first, and want to know which treatment product has the highest potential in the city. They decide that the best way to do that is to apply the Market-Driven Approach. Below is a list with info about Delfinia. Plot and compare the market attractiveness for the markets of all the given treatment products, and based on your plot, discuss what treatment product(s) you would advise them to produce.

Biogas:

- The sole supplier of gas in the country is the company Banoligas. They have a monopoly on all gas resources. Their total sales revenue within the country is €234 million, of which Delfinia composes 21%.
- Banoligas is absolutely not interested in using/selling biogas.
- The market for natural gas is projected to grow by 3.5% in the coming 5 years.

Fertilizer:

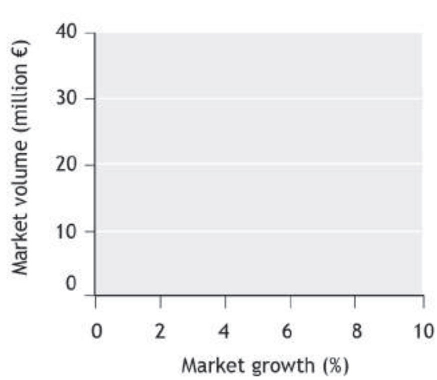
- The Ministry of Agriculture just published a report which predicts that the market for fertilizers will develop by 3% over the next 5 years.
- The price of fertilizer at supplier A is €15 per unit.
- The total sales of fertilizer supplier B is €6.3 million per year.
- Fertilizer company C is a new fast-growing player in the market, and sells €4.4 million per year.
- Fertilizer supplier A sells 1.5 million product units per year.

Solid fuel:

- Since the gas market is dominated by only one player, other companies are starting to look into new fuel options. As a result, the solid fuel market is expected to grow by 5%.
- Solid fuel options in Delfinia are corn hobs and charcoal.
- Each year, farmers sell 800,000 bags of corn hobs.
- The combined amount sold by all the small charcoal sellers is 385,700 kg.
- A bag of corn hobs costs €4, which contains 2 kg. A bag of charcoal costs €3.5, which contains half a kg.

Building materials:

- Due to stagnating infrastructure policies, 1% growth is expected in the building material market in the coming years.
- Only 1.2% of the building material market can be replaced by a faecal sludge treatment product.
- There are many large and small companies that sell all kinds of building materials that could be substituted by a faecal sludge treatment product (e.g. bricks and road construction).
- The total market volume for building materials in Delfinia is €1.14 billion.



Chapter 2.5

Collection and transport technologies

Miriam Englund and Linda Strande

Learning objectives

- Explain why urban areas rely on a range of collection and transport technologies
- Identify existing established technologies for collection and transportation
- Understand considerations for implementation of collection and transport technologies based on the local context
- Give examples of how the design and operation of onsite technologies can ease collection

Textbook

Available at www.sandec.ch/fsm_book

- Strande, L., Ronteltap, M. and Brdjanovic, D. (2014). *Faecal Sludge Management - Systems Approach for Implementation and Operation.*

Free online course (MOOC)

Available at www.eawag.ch/mooc

- *Introduction to Faecal Sludge Management*. MOOC series by Eawag and EPFL. Modules 'Collection and transport technologies', 'Advances in collection', and 'Transport'.

Further Eawag-Sandec publications

Available at www.sandec.ch/fsm_tools

- Gensch, R., Jennings, A., Renggli, S. and Reymond, P. (2018). *Compendium of Sanitation Technologies in Emergencies.*
- Schoebitz, L., Bischoff, F., Lohri, C., Niwagaba, C., Siber, R. and Strande, L. (2017). *GIS analysis and optimisation of faecal sludge logistics at city-wide scale in Kampala, Uganda.* Sustainability, 9(2), 194.
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Additional resources

- Blackett, I. and Hawkins, P. (2017). *FSM Innovation Case Studies - Case Studies on the Business, Policy and Technology of Faecal Sludge Management.* 2nd edition. Bill & Melinda Gates Foundation, Seattle, USA, ISBN 978-1-5136-2513-3.
- Chowdhry, S. and Koné, D. 2012. *Business Analysis of Fecal Sludge Management: Emptying and Transportation Services in Africa and Asia.* Bill & Melinda Gates Foundation, Seattle, USA.
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- Mukheibir, P. (2015). *A guide to septage transfer stations.* Prepared for SNV Netherlands Development Organisation by Institute for Sustainable Futures, University of Technology Sydney.
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Introduction

This chapter presents a brief overview of the collection and transport of faecal sludge. For more details about collection and transport of faecal sludge refer to Chapter 4 in *Faecal Sludge Management - Systems Approach for Implementation and Operation* (Strande *et al.*, 2014).

Urban areas are comprised of different physical and socio-economic circumstances that influence faecal sludge collection and transport, including faecal sludge quantities and qualities, road and containment access, transport distance, and financial flows. Examples of areas within a city with different needs are:

- **Planned middle and high-income areas** with good road infrastructure, and either connections to the sewer or to septic tanks with faecal sludge with a low total solids concentration.
- **Unplanned densely populated low-income areas** with poor access to containments, and pit latrines with faecal sludge with a high total solids concentration.
- **Peri-urban areas** with a low population density with good access to containments, and pit latrines with faecal sludge with a high total solids concentration, with long transport distances to a faecal sludge treatment plant.

Collection and transport services are one part of the full faecal sludge management chain and are crucial to ensure that faecal sludge is safely transported to a treatment plant. However, it is possible that an area served by collection and transport services does not have a treatment plant. Alternatively, it could happen that an area with a treatment plant does not have operational collection and transport services. The collection and transport and the treatment components need to work in parallel, and it is important that economically viable solutions are evaluated. Issues that need to be addressed include suitable discharge fees, business models for the collection and transport service providers, road access to the treatment plant, and distance to the treatment plant.

Collection technologies can, in general, be categorized into manual, mechanized, or manually operated mechanical collection technologies. Emptying services in low-and middle income countries are frequently a mix between mechanical tools and a manual workforce.

Manual collection and transport technologies

Manual collection can be an important part of providing faecal sludge management services. Manual collection and transport technologies can collect sludge with a high totals solid content such as from dry pit latrines when it is not pumpable, and can access narrow lanes and poor containment infrastructures. Refer to Table 4.1 in *Faecal Sludge Management - Systems Approach for Implementation and Operation* for examples of manual technologies. However, manual collection with buckets or shovels can be unsafe and unhygienic, as it frequently involves the workers entering directly into the onsite containment technology. Therefore proper measures for workers' safety need to be put into place. It is important to implement minimum standards and set up systems to ensure their enforcement through licencing, training and capacity development.

Figure 2.5.1 Manual emptying of faecal sludge with buckets and rope into barrels.

Manual collection is frequently used to empty smaller amounts of sludge than mechanical collection. When it is transported manually, it is typically loaded into barrels and transported by carts. Transporting it to a treatment plant through mechanical means can be a challenge, for example, carts are only able to transport the sludge for a few kilometres at an absolute maximum. This frequently results in the discharge of the collected sludge directly into the urban environment or nearby water bodies. Manual collection technologies need to be combined with appropriate transport technologies to ensure that sludge reaches a treatment plant or safe disposal site. A way to upgrade the manual collection and transport is to include human-powered mechanical devices to improve operational efficiency and increase safety and hygienic standards, or to transport the sludge mechanically with pickup trucks.

Mechanical collection and transport technologies

Mechanical collection technologies can pump larger amounts of faecal sludge per trip and per day than manually operated technologies. However, faecal sludge cannot be too thick or it will not be pumpable. Pumps can be mounted on trolleys or carts that are manually operated for increased mobility, or on tractors and trucks, which are the most common mechanized options and allow transportation of the sludge over longer distances. The faecal sludge is pumped from the containment through a hose into a tank. The capacity of these tanks typically ranges between 2 m^3 and 20 m^3. Vacuum trucks often have difficulties accessing onsite sanitation technologies that can only be reached via narrow roads and alleys. In this case, when possible smaller trucks can be used, for example with a capacity between 0.5 m^3 and 4 m^3.

Figure 2.5.2 Faecal sludge truck ready to go to a household for collection.

Manually collected and transported faecal sludge is frequently more expensive per volume than when collected and transported with mechanical technologies. This is due to the time and work spent accessing the onsite sanitation technology and the low volumes of sludge collected and transported for treatment.

Challenges with collection and transportation

Accessibility

Septic tanks are frequently covered over during construction or located under houses, and unlined pit latrines can collapse when emptied. It is important that the containment technology has a robust access point for desludging, which should be integrated into the initial design. For example, the 'U-ACT' project in Kampala built fully lined pit latrines with access for emptying integrated into the structure (for compiled information about the U-ACT project, refer to http://www.dec.ethz.ch/research/tech/urban-affordable-clean-toilets-project--u-act-.html). This allows sludge collection without affecting the integrity and functionality of the structure.

Affordability

For collection and transport services to be viable, the service needs to be affordable for both the customer and the service provider. Transport distances and traffic will increase the required costs for service providers.

Industrial waste

Vacuum trucks can also be used for the collection and transport of industrial waste, so care needs to be taken that this is not also discharged at faecal sludge treatment plants. A manifest system can help address this; see chapter 4 in the book *Faecal Sludge Management - Systems Approach for Implementation and Operation*, and the Karunguzhi case study (2.5.2). An inspection chamber that is manually opened can also help; see the Korhogo case study (2.5.1).

Protection of individuals´ health

It is essential to ensure protection of the public health of workers through measures such as personal protective equipment, vaccinations and training courses. There also needs to be a plan in place to address and prevent spillage during emptying operations.

Pumpability

The thickness of faecal sludge will affect how well it can be pumped for removal from the containment. Manual technologies are required for faecal sludge that has too high solids content or viscosity to be pumped by mechanical technologies.

Solid waste

Solid waste is frequently disposed of using on-site sanitation technologies. Screens can help prevent solid waste from entering collection hoses, but screens will clog. Metal rods or rakes are frequently used to remove solid waste prior to sludge collection. The removed solid waste also needs to be disposed of properly, as it is covered in faecal sludge. To reduce this problem, a solid waste management plan needs to be implemented.

Case study 2.5.1 Collection and transport services in practice: Korhogo, Ivory Coast

The first faecal sludge treatment plant in Ivory Coast was constructed in the northern city of Korhogo in 2017.

Figure 2.5.3 Discharge of faecal sludge collected and transported from households into the inspection chamber at the Korhogo faecal sludge treatment plant.

A number of steps were taken to ensure that the collection and transport services would be viable:

Accessibility

- ONAD (Office National l'Assainissement et du Drainage) together with the city council promotes construction of septic tanks with improved access to enable mechanical emptying, and prevent contamination of water sources.
- Trucks for mechanical emptying come second-hand from Abidjan. They were initially used for clean water, but with modifications are now used for faecal sludge. The number of trucks has doubled since the faecal sludge treatment plant opened.

Affordability

- An emptying association was formed to coordinate and organize the emptying service providers, in close collaboration with the treatment plant management (ONAD) and the city council, to emphasise safe collection and transport.

- ONAD has gradually increased the discharge fee for the service providers to the current level (30-60 US$ depending on volume).
- Emptying service providers report that business is profitable, especially in the rainy season when they make up to 10 trips per day.

Industrial waste

- Many companies augment business with supplying water to construction sites, or emptying other liquid waste streams from industries. From a public and environmental health perspective, this is very high risk, and should not be encouraged anywhere. ONAD is monitoring the situation, enforcing that water with potential cross-contamination is purely for non-potable uses. In addition, all faecal sludge delivered to the treatment plant is first discharged into a tank for inspection to ensure that industrial waste is not also being discharged.

Protection of individual health

- ONAD and the city council are collaborating with the community and the service providers to improve faecal sludge management practices. This is done by awareness campaigns that are promoting safe collection and transport services, and informing about the risks of unhygienic practices and illegal dumping.

Case study 2.5.2 Municipality coordination

In Karunguzhi, India, the municipality operates a call centre to coordinate the collection and transport services of two private companies.

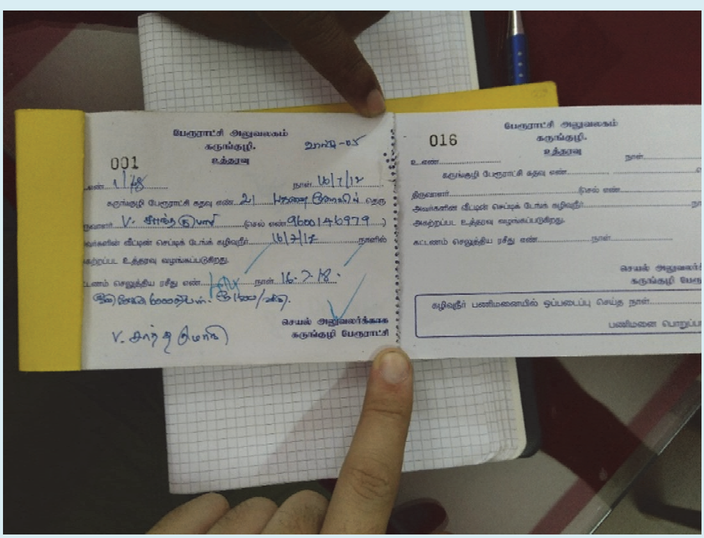


Figure 2.5.4 The voucher used in Karunguzhi, India.

When a customer wants their containment emptied they call the municipality. The municipality assigns the job to one of the emptying companies. The company is given a voucher from the municipality that includes the address of the emptying service, and it is also valid for free discharge of the collected sludge when handed in at the faecal sludge treatment plant. The customer pays the service provider, and the service provider can keep the entire payment. In this way the municipality ensures sludge is delivered to a treatment plant and is not dumped in the environment, and it prevents unknown sources of sludge from being discharged.

Exercises

1. Match the photos (1-4) to the descriptions (a-f). More than one description can apply to each photo.

1)

2)

3)

4)

a) A metal rod for solid waste removal
b) An access point to a containment
c) A manual collection and transport method
d) Personal protective equipment
e) A mechanical collection and transport technology
f) A gauge to measure volume in the tank

2. Illegal dumping of faecal sludge is harmful to public and environmental health.
   a) Name reasons why this practice exists.
   b) Name actions that can be taken to reduce this practice.
3. List the pros and cons of manual and mechanical collection and transport options.
4. In your opinion,
   a) What will drive innovation in collection and transport?
   b) What could be potential solutions for existing challenges with collection and transport of faecal sludge?
5. What factors need to be taken into consideration when designing for a collection and transportation solution for an area?
6. You need to design a faecal sludge collection program for an informal settlement with very thick faecal sludge. The informal settlement is densely populated and most pathways are not navigable by truck. Explain the considerations and your recommendations.
7. Solid waste in onsite containments is very problematic for the collection of faecal sludge; explain how the amount of solid waste in containments could be reduced.
8. Describe the faecal sludge collection and transport process from a household to a treatment facility. List the necessary tasks in chronological order.[1]
9. Personal protective equipment is very important for the emptier to use; what other barriers could be put in place during collection and transport services to protect the public health of the residents and workers?
10. Name the stakeholders and roles involved in the collection and transport operation.
11. Give the reason why unlined pit latrines are not recommended, and suggest modifications for an improved design.
12. The discharge fee at the faecal sludge treatment plant in the area where you are working is too high for collection and transport services to afford. Therefore, illegal dumping in nearby canals, rivers and fields is common. The trucks that do reach the treatment plant also complain about the distance from the city. Discuss improvements to the infrastructure that should be implemented.

[1] Adapted from *Introduction to Faecal Sludge Management: Trainer manual (2016)* by CAWST and Eawag-Sandec. www.cawst.org and www.sandec.ch. Licensed under http://creativecommons.org/licenses/by/4.0/

13. Read the following scenarios and propose solutions to resolve them[2].

Scenario	Solution
Households do not have enough money to pay for the collection and transport service.	
Faecal sludge is too thick for the collection and transport service to pump out. The onsite sanitation technology is close to overflowing.	
The faecal sludge treatment facility (owned by the public sector) is charging a discharge fee which private service providers cannot afford. As a result, they are illegally dumping faecal sludge into the street, nearby canals, rivers or lakes. Sometimes they dump the faecal sludge into a sewer manhole, which is not a sustainable option as it can cause wastewater treatment facilities to fail.	
Households cannot afford the fee charged by the service providers for emptying because of their transport costs to the treatment facility.	
The household is located in an informal settlement. The pathways are too narrow and not maintained. It is difficult for a vacuum truck to access the household.	

[2] Adapted from *Introduction to Faecal Sludge Management: Trainer manual (2016)* by CAWST and Eawag-Sandec. www.cawst.org and www.sandec.ch. Licensed under http://creativecommons.org/licenses/by/4.0/

Chapter 3.1

Overview of treatment technologies

Miriam Englund and Linda Strande

Learning objectives

- Explain the different levels of technology development
- List technologies based on level of technology development
- Group technologies by treatment objective

Textbook

Available at www.sandec.ch/fsm_book

- Strande, L., Ronteltap, M. and Brdjanovic, D. (2014). *Faecal Sludge Management - Systems Approach for Implementation and Operation.*

Free online course (MOOC)

Available at www.eawag.ch/mooc

- *Introduction to Faecal Sludge Management.* MOOC series by Eawag and EPFL. Module ´Overview of treatment technologies´ and the full Week ´Integrated approach to faecal sludge management´.

Further Eawag-Sandec publications

Available at www.sandec.ch/fsm_tools

- Tilley, E., Ulrich, L., Lüthi, C., Reymond, P. and Zurbrügg, C. (2014). *Compendium of Sanitation Systems and Technologies. 2nd edition.* Dübendorf, Switzerland, Swiss Federal Institute of Aquatic Science and Technology (Eawag). www.sandec.ch/compendium

Additional resources

- Mara, D. (2013). *Domestic wastewater treatment in developing countries*. London, Routledge.
- Metcalf & Eddy (2014). *Wastewater Engineering: Treatment and Resource Recovery.* 5th Edition, McGraw-Hill, New York.
- Tayler, K. (2018). *Faecal sludge and septage treatment – a guide for low and middle income countries*. Rugby, UK, Practical Action Publishing.
- Von Sperling, M. and de Lemos Chernicharo Augustos, C. (2005). *Biological Wastewater Treatment in Warm Climate Regions.*

Introduction

When selecting an appropriate technology for faecal sludge treatment, it is very important to consider whether technologies are established, being transferred from other sectors, or are still at the innovative phase of development. Technologies are classified based on the level of adaption, research, innovation, and expert knowledge that is required for successful implementation. Technologies are considered **established** if their design and their operational and maintenance guidelines can be readily recommended. **Transferring** technologies are still in the process of being adapted for faecal sludge management from other sectors such as wastewater treatment or solid waste management. **Innovative** technologies are promising and potentially ready to be scaled up, but are currently still at the pilot scale of development. Table 3.1.1 summarizes faecal sludge treatment technologies and their level of development. The implementation of transferring and innovative technologies has an increased risk due to less operating experience. Hence, technology development needs to be managed during operation. This could be done through, for example, public or private partnerships or research collaboration with universities. The first step in the engineering design approach is defining the treatment objectives based on effluent and treated sludge standards, resource recovery and/or disposal options. Selecting technologies is also based on factors such as cost, operational and maintenance requirements, and faecal sludge quantities and qualities (Q&Q) that need to be treated. For more information about sanitation planning, refer to chapters 14-17 in *Faecal Sludge Management – Systems Approach for Implementation and Operation* (Strande *et al.* 2014) and Week 4 in *Introduction to faecal sludge management,* MOOC series by Eawag and EPFL.

Table 3.1.1 The three levels of treatment technology development and their respective technologies.

Established	Transferring	Innovative
settling-thickening tanks	anaerobic digestion	ammonia treatment
unplanted drying beds	incineration	black soldier fly (BSF)
planted drying beds	lime treatment	thermal drying
co-composting	mechanical dewatering	vermicomposting
deep row entrenchment	pelletizing	
	solar drying	

Accurate estimates of Q&Q of influent faecal sludge can be very difficult to make. However, they are crucial for correctly sizing technologies. Qualities are important in order to evaluate which technologies will be appropriate along the entire service chain. For example, the level of stabilization or digestion of faecal sludge is important for producing biogas, the suspended solids content is important for selecting a settling-thickening tank, and the per cent of solids is important for producing dry combustion fuels.

Influent and effluent values for a treatment plant are important to consider, as well as values before and after each step in the treatment chain. It is also important to track actual values from a mass balance perspective. Many terms that are commonly used in wastewater treatment are not directly applicable to faecal sludge management, for example, per cent removals. When considering settling-thickening tanks or drying beds, matter is not 'removed' as is the case during biological degradation in the secondary treatment of wastewater (e.g. organic matter being converted to CO_2). Solids and organics are, for the most part, fully conserved in either the solids or liquid streams. In addition, since influent concentrations of constituents in faecal sludge can be quite high, stating per cent 'removals' can be very misleading, as the effluent frequently still has higher concentrations than typical wastewater and requires further treatment. For example, consider the discharged faecal sludge concentration of 72,000 mg TSS/L; after dewatering and drying treatment with a 99 % removal, the effluent still has 720 mg TSS/L (!) This is significantly higher than typical discharge standards (10–100 mg TSS/L).

Treatment technologies are usually linked together in series to fulfil multiple treatment objectives. For example, incoming faecal sludge with a very low solids content is more suitable to be treated with a settling-thickening tank (dewatering) prior to being applied to drying beds (dewatering and drying). Figure 3.1.1 presents an example of a treatment plant process flow, and the treatment objectives achieved with each technology.

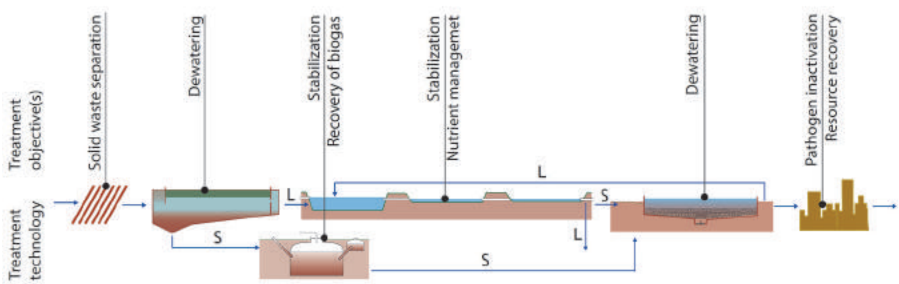


Figure 3.1.1 Example of a process flow of a faecal sludge treatment plant.

Case study 3.1.1 Planning of faecal sludge treatment systems - Sircilla, India

Provided by CDD (Consortium for DEWATS Dissemination) Society

CDD society designed a faecal sludge treatment plant of 18 m^3/day capacity to serve a population of 100,000 in Sircilla, a town in the Indian state of Telangana. The town has a semi-arid climate. Sircilla has no sewer network and is fully served by onsite sanitation systems. The objectives are to use treated solids as soil amendment and the treated liquid as reclaimed water for irrigation. Priority was given to low costs, and low electricity and maintenance requirements. Further, a robust process flow was adopted to handle the highly variable faecal sludge quantities and qualities. The treated faecal sludge must meet current effluent and solids discharge standards set by the Central Pollution Control Board, namely BOD < 20 mg/L and COD < 50 mg/L.

The treatment process includes screening to remove solid waste, Anaerobic Stabilization Reactor (ASR) for stabilization, unplanted sludge drying beds for dewatering. The dewatered solids from the unplanted drying beds are either co-composted or thermal dried in a solar heated greenhouse to inactivate pathogens prior enduse. The liquid stream from dewatering unit is treated by Anaerobic Baffled Reactor (ABR), Anaerobic Filter (AF), Planted Gravel Filter (PGF), Pressure Sand and Activated Carbon Filter (PS & ACF) and finally disinfected in polishing ponds (PP). See Figure 3.1.2 for the process flow of the treatment.

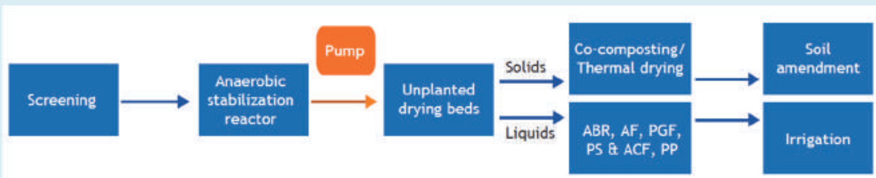


Figure 3.1.2 Process flow of the concept FSTP proposed by CDD Society in Sircilla, India.

The ASR was adopted in order to treat less stabilized faecal sludge from onsite sanitation systems due to proposed scheduled emptying in the town. Further, the initial concept included treating faecal sludge in all the modules by gravity which needed an elevation of six meters from inlet to outlet of the plant. Since this would have resulted in escalation of capital cost, a pump was added for conveying the stabilized sludge from the ASR to the unplanted drying beds. The additional cost of this pump was offset by the removal of the excavation cost. The treatment plant contains two parallel streams – each stream designed to handle 9 m^3/day of faecal sludge, see dimensions in Table 3.1.1.

Table 3.1.2 Dimensions for a 9 m^3 treatment plant. C1: chamber one, C2: chamber two, C3: chamber three, HLR: hydraulic loading rate.

Treatment units	No. of units	Sizes L × W × H [m]	Influent BOD, COD [mg/L]	Effluent BOD, COD [mg/L]
Screen	1	3 × 0.6 × 0.5		
Anaerobic stabilization reactor	1	C1: 4 × 2 × 2.2 C2: 5.2 × 7.3 × 2 C3: 5.2 × 1.6 × 1.2		
Unplanted drying bed	12	6.25 × 4.8 × 1.2 HLR: 0.3 m		
Anaerobic baffled reactor	1	0.8 × 1.3 × 2.1 (2 chambers)	200, 400	30, <250
Anaerobic filter	1	1 × 1.3 ×x 2 (3 chambers)	200, 400	30, <250
Planted gravel filter	1	7.5 × 7.0 × 0.6	30, 250	<20, 100
Sand carbon filter	1	0.8 ⌀ × 2 h	20, 100	<15, 50
Polishing pond (elliptical shape)	1	2.4 × 1.2 (a, b)	15, 50	<15, <50

Exercises

1. The development for faecal sludge treatment technologies is divided into three different levels.
   a) Why are treatment technologies divided into these levels?
   b) Name the three levels of development for faecal sludge treatment technologies. Explain with one sentence what each level means.
2. Name three treatment technologies that have nutrient management as a treatment objective.
3. Treatment technologies have different fields of application. Propose treatment technology options for:
   a) Faecal sludge that has not undergone significant stabilization
   b) Faecal sludge stabilized in the containment
4. Name three transferring treatment technologies.
5. It is important to consider the mass balance for each technology in a treatment chain in order to know the loads moving from one technology to another. Assume an unplanted drying bed with 25 m x 7 m area, loaded with 52.5 m^3 faecal sludge with a concentration of 80 g TS/L, resulting in a 8 cm dewatered sludge layer with a concentration of 292 g TS/L. Further assume an effluent concentration of 3 g TS/L.
   a) What is a mass balance? And why is it useful?
   b) Draw a mass balance situation sketch. Assume no evaporation takes place.
   c) How much leachate would the unplanted drying bed produce with a kg TS mass balance?
   d) Draw a new mass balance situation sketch including evaporation. How does evaporation affect the system?
6. A large brick factory is located close to a community, and a demand for faecal sludge as a fuel was identified. Clearly state the treatment objectives and a suitable treatment chain.
7. Give three examples of potential mechanical dewatering treatment technologies for faecal sludge that are being transferred from wastewater treatment.
8. Mechanical faecal sludge dewatering is a transferring treatment technology and still needs some additional research for optimal use in faecal sludge treatment. What are the main constraints with mechanical dewatering in faecal sludge treatment?
9. In theory, when designing faecal sludge treatment, effluent and treated sludge standards are the target. In some cases, stringent standards are challenging to fulfil, which leads to designs with expensive and high technology treatment options. High technology treatment could be difficult to integrate in areas with a lack of consistent electricity supply or adequate funds for skilled staff and maintenance work. Argue in 200 words for the relevance of protecting public health and therefore designing treatment that can realistically be implemented and operated. Include a discussion about the trade-off between high technology treatment solutions vs. gravity flow treatment.

10. You and a colleague are designing a faecal sludge treatment plant in a densely populated area. Close to the community there is a small-scale vegetable farm. Your colleague shows you his suggestion, see Figure 3.1.3. The treatment objective is pathogen inactivation and therefore he proposes a combination of lime treatment and vermifiltration. This also reduces the amount of solids and results in soil amendment for the vegetable farm.
   c) What are the challenges with his suggestion?
   d) How could the process flow in Figure 3.1.3 be rearranged for a better treatment performance?

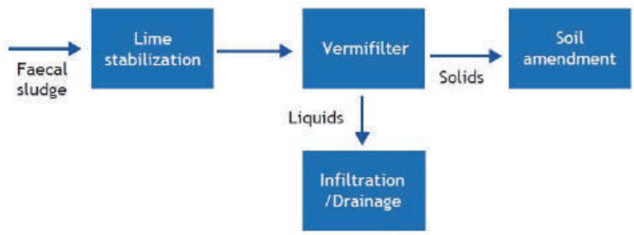


Figure 3.1.3 Process flow diagram of a proposed faecal sludge treatment solution.

11. Use the engineering design approach to select which faecal sludge treatment technology or combination of technologies you would implement in the following scenarios. Your answer should include an explanation of why you selected the technology or technologies, including resource recovery and treatment objectives.
   a) You need to design a treatment plant for a peri-urban community with lots of available land. The climate is semi-arid. Goat and cattle farming are an important industry, as is the farming of fodder crops. A recent census reported that 85 % of onsite systems are septic tanks and 15 % are pit latrines.
   b) A densely populated urban area requires a treatment plant. A large market is located in the community, which produces a steady stream of organic waste. The market has a high demand for propane cooking fuel. About 40 % of the community is serviced by public toilets. The climate is tropical.
   c) In a city located along a river, horse-riding tourism is very common and the horse owners are struggling to find food for the horses. They currently use grass cut from the riverside but it is not adequate, especially during the dry season. The hotels for the tourism bring a lot of faecal sludge from septic tanks with a large proportion of greywater that is currently discharged into the river. Most of the septic tanks are installed without an overflow system and quickly fill up.
   d) The inhabitants in a dense urban area are farmers. They are struggling to grow their crops due to the poor soil structure. There is a large market located in the community, which produces a steady stream of organic waste. The climate is tropical.
   e) A small city in West Africa is considering how to manage their faecal sludge. The majority of onsite sanitation systems in the city are pit latrines. The main economic activity is in service industries, and there is lots of subsistence farming. The climate is arid. The city has no space for disposal, and there is a strong taboo on faecal sludge use.

12. In Figure 3.1.4 you can see a configuration of a faecal sludge treatment plant. Write down each technology's treatment objective and discuss the overall treatment set-up.

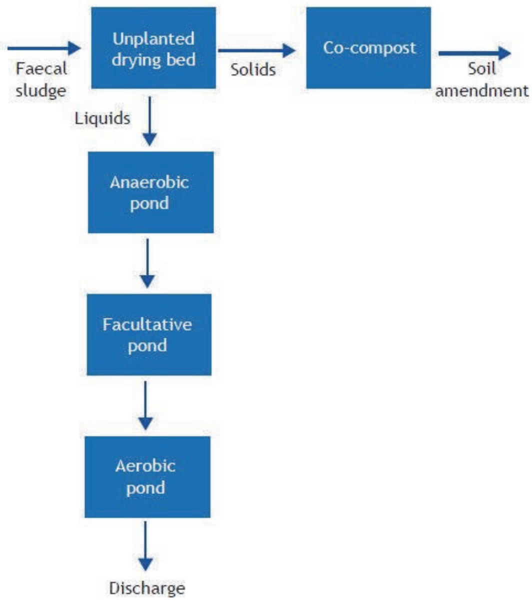


Figure 3.1.4 Process flow diagram of a faecal sludge treatment plant.

13. Each treatment technology has its purpose, but it is also important that the selected treatment technologies combine well together. Look at Figure 3.1.5 and point out mistakes that the process engineer has made in the planning.

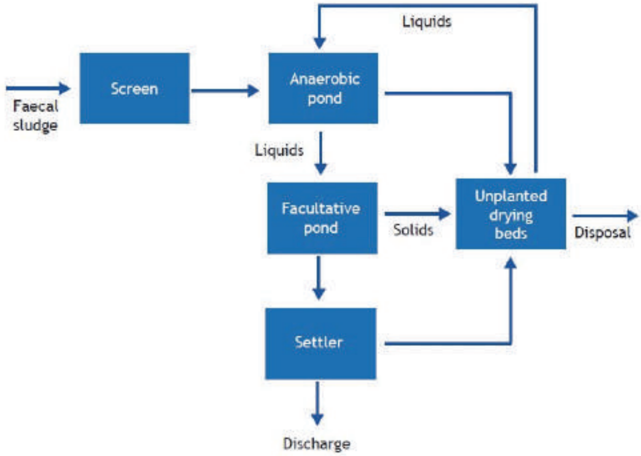


Figure 3.1.5 Process flow diagram of a faecal sludge treatment plant.

Technology

Chapter 3.2

Settling-thickening tanks

Miriam Englund and Linda Strande

Learning objectives

- Explain the treatment process and operation
- Discuss the operation and maintenance requirements
- Name the design parameters

Textbook

Available at www.sandec.ch/fsm_book

- Strande, L., Ronteltap, M. and Brdjanovic, D. (2014). *Faecal Sludge Management - Systems Approach for Implementation and Operation*.

Free online course

Available at www.eawag.ch/mooc

- *Introduction to Faecal Sludge Management*. MOOC series by Eawag and EPFL. Module ´Settling-thickening tanks´.

Further Eawag-Sandec publications

Available at www.sandec.ch/fsm_tools

- Heinss, U., Larmie, S.A. and Strauss, M. (1998). *Solids Separation and Pond Systems for the Treatment of Faecal Sludges In the Tropics. Lessons Learnt and Recommendations for Preliminary Design.*
- Heinss, U., Larmie, S.A. and Strauss, M. (1999). *Characteristics of faecal sludges and their solids-liquid separation.* Eawag/Sandec: Janeiro.
- Tilley, E., Ulrich, L., Lüthi, C., Reymond, P. and Zurbrügg, C. (2014). *Compendium of Sanitation Systems and Technologies. 2nd edition.* Dübendorf, Switzerland, Swiss Federal Institute of Aquatic Science and Technology (Eawag). www.sandec.ch/compendium

Additional resources

- Metcalf & Eddy (2014). *Wastewater Engineering: Treatment and Resource Recovery.* 5th Edition, McGraw-Hill, New York.
- Reddy, M. (2013). *Standard Operating Procedures*. University of KwaZulu-Natal.
- Von Sperling, M. and de Lemos Chernicharo Augustos, C. (2005). *Biological Wastewater Treatment in Warm Climate Regions.*

Introduction

The main treatment objective of settling-thickening tanks is solid-liquid separation; pathogen inactivation does not occur, and both liquid effluent and settled sludge require further treatment. Thickened sludge is normally removed after 5 to 30 days by a combination of pumps, front-loaders, and/or manually with shovels. The loading period should be adjusted with the TSS in the supernatant layer. If the outlet's TSS concentration is too high, adjustments are required. There are normally two parallel tanks to allow for sludge removal and maintenance.

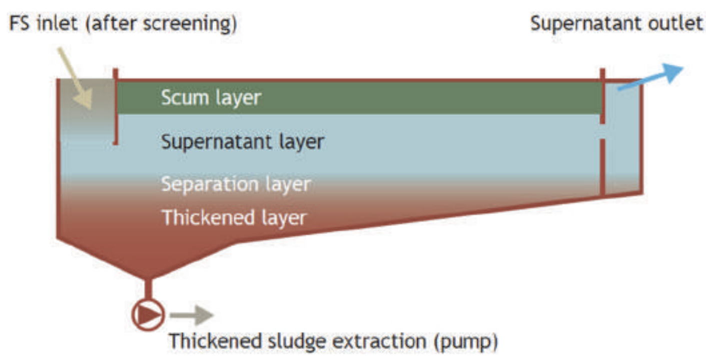


Figure 3.2.1 Schematic of the settling-thickening tank configuration

Settling-thickening tanks have an inlet with a baffle to ensure quiescent flow, and an outlet with a baffle to allow only the supernatant to pass through the outlet. The floor is commonly either sloped so sludge can be pumped out, or else flat with access for removal by a front loader. Total suspended solids settle out into the thickened layer, and fats, oils and grease float to the scum layer.

Prior to designing a settling-thickening tank, tests should be conducted with Imhoff cones to determine the settleability of the specific sludge. Settleability (recommended to be <100 mL/g TSS for settling) is determined by the Sludge Volume Index (SVI) and is estimated by settling of 1 litre of faecal sludge in Imhoff cones or columns for 30 to 60 minutes. The Sludge Volume Index is then calculated from the volume that settles at the bottom of these Imhoff cones divided by the initial total suspended solids concentration.

$$SVI = \frac{\text{Volume settled FS}}{c_{TSS}} \ [\text{mL/g}]$$

In general, it has been observed that sludge that is more stable settles better than sludge that has been stored in the containment for shorter periods of time. However, more research is needed to give more precise guidelines. Treatment performance can be measured by TSS concentrations in the effluent/supernatant. At the Lubigi wastewater and faecal sludge treatment plant in Kampala, Uganda, the settling-thickening tanks achieve 60% removal (settling efficiency).

Sizing settling-thickening tanks

The approach taken for the sizing of settling-thickening tanks is summarized in Table 3.2.1.

Table 3.2.1 Step-by-step approach for the design of settling-thickening tanks

Step 1	Establish design criteria
Step 2	Calculate surface area
Step 3	Calculate thickened sludge volume
Step 4	Determine tank dimensions
Step 5	Configure inlet and outlet
Step 6	Operation and maintenance

Step 1: Establish design criteria

The design of settling-thickening tanks is based on the TSS concentration of the incoming sludge and its settleability. Faecal sludge can either be discharged directly to the settling-thickening tanks, in which case following the Q&Q method to determine quantities and qualities and quantities would be most appropriate, or can be loaded using other technologies.

SVI: Sludge Volume Index [mL/g]
Q_S: Daily inflow of faecal sludge [m^3/d]
C_{TSS_in}: TSS concentration of influent sludge [kg TSS/m^3]
f_{op}: Delivery/operating days per year [d]
e: Settling efficiency [-] (should be designed as 80%; in reality a reduction will probably occur, so a safety factor is recommended).

Step 2: Calculate surface area

The surface area is calculated based on the peak flow to ensure enough time for the particles to settle.

SA: Surface area of the tank [m^2]
Q_p: Influent peak flow [m^3/h]
V_u: Settling velocity [m/h]
C_p: Peak flow coefficient [-]
Q_S: Daily inflow of faecal sludge to the settling-thickening tank [m^3/d]
h: Number of operating hours of the treatment plant per day [h/d]

$$SA = \frac{Q_p}{V_u} \ [m^2]$$

$$Q_p = \frac{Q_S \times C_p}{h} \ [m^3/h]$$

Based on existing experience, the settling velocity can be estimated as 0.5 m/h in rectangular settling-thickening tanks to treat faecal sludge with a SVI of less than 100 mL/g TSS.

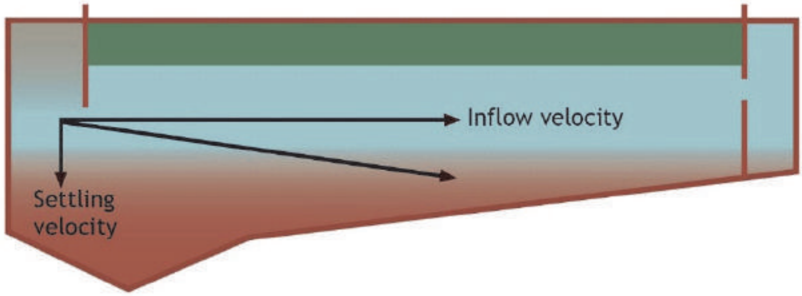


Figure 3.2.2 Schematic of the relation between settling velocity and inflow velocity for a particle to settle in the tank

The tank is designed based on the desired removal of particles from the supernatant to the solids layer. In order for the particles to settle in the tank, a settling velocity greater than the inflow velocity is required, as shown in Figure 3.2.2.

The recommended ratio between width and length is between 1:10 and 1:5. Lower settling velocities require longer tanks for particles to settle and remain in the tank. Depending on the planned operation of the tank, the design will vary. Manual emptying, either by truck or pump, of solids will result in different layouts and loading and discharge cycles. The calculated area should be doubled so that two parallel-operated settling-thickening tanks can receive discharged faecal sludge.

Step 3: Sizing of thickened sludge layer

The thickened sludge layer depth will vary with TSS concentration and will govern the design of the settling-thickening tank.

V_t: Volume of thickened sludge storage zone [m^3]
Q_S: Daily inflow of faecal sludge to the settling-thickening tank [m^3/d]
C_{TSS_in}: TSS concentration of incoming faecal sludge [kg TSS/m^3]
C_{TSS_out}: TSS concentration of thickened faecal sludge [kg TSS/m^3]
e: Settling efficiency
N: Faecal sludge loading time [d]
d_t: Thickened faecal sludge depth [m]

$$V_t = \frac{Q_S \times C_{TSS\_in} \times e \times N}{C_{TSS\_out}} \text{ [m}^3\text{]}$$

$$d_t = \frac{V_t}{SA} \text{ [m]}$$

To find out how much sludge has accumulated in the thickened sludge layer, the average daily inflow is used. However, in reality the faecal sludge loading period (N) is also determined by a trade off or consideration of the treatment technologies that then follow, although it should not exceed four weeks. As a principle, the more time the thickened faecal sludge has to compact, the more challenging the removal with pumps will be. Expected TSS concentrations in the solids and supernatant layers can be estimated by using Imhoff cones or column testing prior to designing the system.

Step 4: Determine tank depth

The total depth is established by assumptions of the scum, supernatant and separation layer depth. Nevertheless, excavation costs for building tanks are commonly high and are a limiting factor in the maximum depth.

Table 3.2.2 Preliminary guidelines based on studies in Accra and the respective sludge layer and its recommended depth (Heinss *et al.*,1998).

Sludge layer	Depth of respective layer [m]
Scum	0.4 – 0.8
Supernatant	0.5
Separation	0.5
Thickened sludge	To be calculated, from Step 3.

D_t: Total tank depth [m]
V_t: Volume of thickened sludge storage zone [m^3]
SA: Surface area of the tank [m^2]

$$D_t = \frac{V_t}{SA} + \sum respective\ layer\ depths\ [\mathrm{m}]$$

Step 5: Configure inlet and outlet

Without an adequate inlet and outlet design, turbulent flow will disrupt the solid-liquid separation and the risk of short circuiting increases. The outlet needs to be placed horizontally lower than the inlet to avoid backflow. The baffles are important to stop scum leaving the tank with the outlet and slowing down the influent streams. Also, an inlet chamber is useful to slow down and decrease the inflow forces of the discharged faecal sludge.

Step 6: Operation and maintenance

Constant monitoring and adaption accordingly are always required. In the design phase a series of assumptions are made in order to design the operation. The operation cycle consists of 1) faecal sludge loading, 2) thickened faecal sludge compaction, and 3) bottom sludge and scum removal.

Pump failure is a common issue so it is important that it is installed in such a way that it can be accessed without pumping out the tank contents. Pumps should be selected based on the solids concentration of the thickened layer and available energy source. To alleviate frequent problems with pumping, solids are frequently removed by front loaders. Designing for manual removal using shovels is not recommended due to the difficult nature of removal.

The TSS concentration of the supernatant will guide you in the treatment performance of the settling-thickening tank. If the TSS concentration is not suitable for the subsequent effluent treatment technology, a change in design, incoming faecal sludge, inlet/outlet design and/or more frequent desludging might be required.

Example 3.2.1 SVI test

With 260 mL/L faecal sludge settled after 60 minutes and 7.4 g TSS/L faecal sludge the SVI was determined.

$$SVI = \frac{\text{Volume settled FS}}{c_{TSS}} = \frac{260\ \text{mL/L}}{7.4\ g\ TSS/L} = 35.1\ [\text{mL/g}] << 100\ \text{mL/g TSS.}$$

100 mL/g TSS is the threshold for wastewater sludge. Faecal sludge with an SVI lower than 100 mL/ g TSS can be considered suitable for settling-thickening technologies. Other criteria such as adequate sampling numbers, information about faecal sludge origin and stabilization level are also used to carry out a proper evaluation of settling-thickening as an appropriate treatment technology.

Example 3.2.2 Sizing of a settling-thickening tank

6 days a week 150 m^3/day of faecal sludge is discharged into a faecal sludge treatment plant. The treatment plant is open 9 hours a day, and has a peak flow of 20 m^3/h. The faecal sludge is discharged into the settling-thickening tank during one working week (6 days). The incoming faecal sludge has an average TSS of 6 g TSS/L, and thickened TSS concentration of 60 g TSS/L. The SVI test showed good results, and there are a settling efficiency of 80% and a settling velocity of 0.5 m/h. Calculate the required surface area and tank dimensions for the settling-thickening tank.

Solution:
Determine the required surface area for the particles to settle during peak flow.

$$SA = \frac{Q_p}{V_u} = \frac{20\ [\frac{m^3}{h}]}{0.5\ [\frac{m}{h}]} = 40\ \text{m}^2$$

A length-to-width ratio of 1:10 results in a 4 m-wide and 10 m-long tank, and to allow for compaction and desludging, two parallel tanks → 40 × 2 = 80 m^2 surface area.

The next step is to calculate the required thickened faecal sludge (layer) volume and to determine the total tank depth.

$$V_t = \frac{Q_s \times c_{TSS\_in} \times e \times N}{c_{TSS\_out}} = \frac{150[\frac{m^3}{d}] \times 6[\frac{kg\ TSS}{m^3}] \times 0.8[-] \times 6[d]}{60\ [\frac{kg\ TSS}{m^3}]} = 72\ \text{m}^3 \text{ of thickened faecal sludge.}$$

We can assume the scum layer to be 0.4 m.

$$D_t = \frac{V_t}{SA} + \sum respective\ layer\ depths = \frac{72[m^3]}{40[m^2]} + 0.4\,[m] + 0.5[m] + 0.5[m] = 3.2\ m$$

Remember that the principle of settling-thickeninig tanks requires a smooth flow and without it the treatment will not be satisfactory. Therefore, baffles and the correct inlet and outlet configurations are crucial. For the incoming faecal sludge to settle, it is necessary to have 2 parallel tanks of 40 m^2 each, with a length of 10 m, width of 4 m and depth of 3.2 m.

Exercises

1. What is the treatment objective of settling-thickening tanks? Give one example of why you want to achieve it.
2. Settling, thickening and flotation are the three fundamental mechanisms describing how settling-thickening tanks operate. What is the end result of the three fundamental mechanisms?
3. For the construction of settling-thickening tanks, it is important to size the faecal sludge inlet and supernatant outlet properly to avoid inadequate treatment. Explain the purpose of a baffle, and how the flow characteristics affect the settling.
4. Depending on the age of the faecal sludge, the solid-liquid separation performance varies. Start with explaining why and give an example of a faecal sludge source where decreased solid-liquid separation can occur.
5. For the design of settling-thickening tanks, we are interested in the TSS. The TSS will settle in the bottom which will increase the volume of the thickened faecal sludge and this will govern the total tank volume. How many percent of the total suspended solids typically stay in the tank and how much passes out of the tank with the effluent?
6. The main treatment objective for settling-thickening tanks is solid-liquid separation. Both effluent and solids require further treatment. Give an example of further treatment and what treatment objectives they should have, depending on the enduse.
7. Why is a loading cycle longer than 10 days not recommended when unloading is carried out using pumps?
8. If pumps are not used for moving the settled sludge for further treatment, how is it done?
   a) Describe how emptying without pumps is typically done.
   b) List two pros and two cons for manual vs. mechanical faecal sludge removal.
9. How can settleability be tested prior to designing a settling-thickening tank?
10. Design parameters specific to settling-thickening tanks are settling velocity and settling efficiency. How can settling efficiency be measured?
11. Monsoons, dry seasons and many other weather conditions will affect treatment performance. How can thickened sludge volume, tank dimensions and inflow velocity be affected by increased rainfall
12. Draw a settling-thickening tank with lines depicting flows and explain the impact that decreased settling velocity will have on the flow velocity and treatment performance.
13. How could a design allowing for manual emptying vary from one designed for pumping? And how will the operation and maintenance be affected?
14. Draw a mass flow diagram of the incoming faecal sludge to a settling-thickening tank and its outputs. Then explain how the effluent treatment will be affected by decreased settling efficiency.

Design and calculate

15. Faecal sludge characteristics are highly variable, and even with a proper assessment of quantities and qualities (Q&Q), it is still challenging to accurately estimate loadings. For example, in one faecal sludge treatment plant the settling-thickening tank was designed for 100 m^3 FS/day, 700 kg TSS/day, a thickened sludge concentration of 110 g TSS/L, and a loading period of 10 days. However, during operation it actually received 340 m^3 FS/day and 1,700 kg TSS/day. The peak inflow was designed as 20% higher than the average flow, which correlated with reality. The faecal sludge treatment plant is open 6 days a week and 10 hours per day. The design was based on 80% settling efficiency, and an Imhoff cone test showed an actual TSS concentration of the thickened sludge of 140 g TSS/L. Assume a settling velocity of 0.5 m/h.
    a) Calculate the tank dimensions needed for both scenarios (design and operational values).
    b) List the operation and maintenance required for settling-thickening tanks.

16. You are in charge of a bench scale test of the sludge settleability. You conduct a SVI test with sludge from septic tanks which has a TSS concentration of 7.2 g/L. The results were that after 60 minutes the settled volume was 220 mL/L. Now calculate the SVI and argue if it is reasonable as settling, and whether the design of a settling-thickening tank is reasonable.

17. You have been asked to send in a design suggestion for a settling-thickening tank. The tank needs to be dimensioned to receive 300 m^3 faecal sludge daily, and you can assume a peak flow of 400 m^3 faecal sludge daily, with 10 h operation per day. Assume the values in the table below.

Sludge layer	Depth [m]	TSS [kgTSS/m^3]
Scum	0.5	135
Supernatant	0.5	4
Separation	0.5	50
Thickened sludge	To be calculated	120

Also assume:

Settling velocity = 0.5 m/h

Settling efficiency = 80 %

Incoming TSS = 7 kg TSS/m^3

Calculate the tank depth required for a loading period of:

a) 30 days
b) 6 days
c) Discuss which loading period is most appropriate for these faecal sludge characteristics. Also discuss how the TSS concentration of the supernatant could be affected by an increased loading period.

18. The hotels close to the treatment plant where you work are closed for renovation, so no more FS from the hotels is currently being discharged. The hotels have septic tanks that are normally frequently emptied with typically dark brown sludge without a strong odour. Following this change, the sludge properties at your treatment plant have also changed, since the treatment plant now only receives faecal sludge with a lighter brown colour and a strong smell. You have also observed that the settling velocity has increased. Explain what has happened and how this will affect the tank operation (hint: faecal sludge qualities and settling velocity).

19. In your city the average total solids concentration for pit latrines is 14 g TS/L and slightly lower for septic tanks. A lot of illegal dumping of faecal sludge is taking place and a volume of 140 m^3 per day needs be allocated to treatment. A new treatment plant will be built in your city, and you have been asked to propose a design for a settling-thickening tank for faecal sludge with average TSS concentration = 10 g TSS/L and thickened sludge TSS concentration = 120 g TSS/L.

    Peak flow coefficient: 1.6
    Settling efficiency: 80 %
    The treatment plant is scheduled to operate 7 hours per day, 6 days a week.
    The Sludge Volume Index is 25 mL/g.

    Make reasonable assumptions for data that is not given.

Technology

Chapter 3.3

Unplanted drying beds

Miriam Englund and Linda Strande

Learning objectives

- Explain the treatment process and operation
- Discuss the operation and maintenance requirements
- Name the design parameters

Textbook

Available at www.sandec.ch/fsm_book

- Strande, L., Ronteltap, M. and Brdjanovic, D. (2014). *Faecal Sludge Management - Systems Approach for Implementation and Operation.*

Free online course

Available at www.eawag.ch/mooc

- *Introduction to Faecal Sludge Management.* MOOC series by Eawag and EPFL. Module ´Unplanted drying beds´.

Further Eawag-Sandec publications

Available at www.sandec.ch/fsm_tools

- Cofie, O., Agbottah, S., Strauss, M., Esseku, H. and Montangero, A. (2006). *Solid-liquid separation of faecal sludge using drying beds in Ghana: implications for nutrient recycling in urban agriculture.* Water Research. 40(1):75-82.
- Heinss, U., Larmie, S.A. and Strauss, M. (1998). *Solids Separation and Pond Systems for the Treatment of Faecal Sludges in the Tropics. Lessons Learnt and Recommendations for Preliminary Design.* Eawag-Sandec report No. 05/98
- Koné, D., Cofie, O., Zurbrügg, C., Gallizzi, K., Moser, D., Drescher, S. and Strauss, M. (2007). *Helminth eggs inactivation efficiency by faecal sludge dewatering and co-composting in tropical climates.* Water research, 41(19), 4397-4402.
- Kuffour, A.R., Awuah, E., Anyemedu, F.O.K., Strauss, M., Kone, D. and Cofie, O. (2009). *Effect of using different particle sizes of sand as filter media for dewatering faecal sludge.* Desalination, 248(1-3), 308-314.
- Seck, A., Gold, M., Niang, S., Mbéguéré, M. and Strande, L. (2015). *Faecal sludge drying beds: Increasing drying rates for fuel resource recovery in Sub-Saharan Africa.* Journal of Water, Sanitation and Hygiene for Development. 5(1), 72-80.

- Tilley, E., Ulrich, L., Lüthi, C., Reymond, P. and Zurbrügg, C. (2014). *Compendium of Sanitation Systems and Technologies.* 2nd edition. Dübendorf, Switzerland, Swiss Federal Institute of Aquatic Science and Technology (Eawag). www.sandec.ch/compendium

Additional resources

- Mara, D. (2013). *Domestic wastewater treatment in developing countries*. London, Routledge.
- Metcalf & Eddy (2014). *Wastewater Engineering: Treatment and Resource Recovery.* 5th Edition, McGraw-Hill, New York.
- Von Sperling, M. and de Lemos Chernicharo Augustos, C. (2005). *Biological Wastewater Treatment in Warm Climate Regions*. Volume II. IWA Publishing.

Introduction

The main treatment objective of unplanted drying beds is the dewatering and drying of faecal sludge; they are not intended for pathogen inactivation. The leachate requires further treatment, see chapter 3.7 on effluent treatment, since the effluent nutrient and organic content from unplanted drying beds can be higher than for typical wastewater treatment influent. The dewatered and dried solids might need further treatment depending on the enduse.

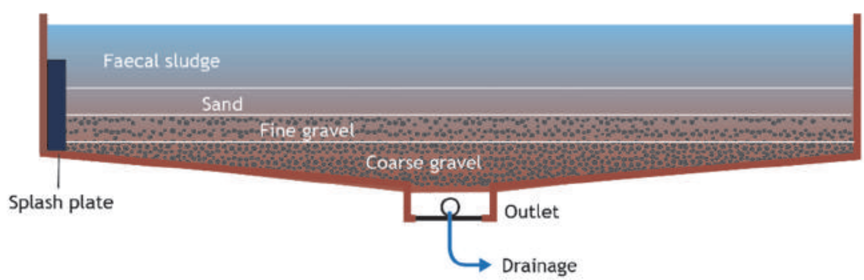


Figure 3.3.1 Cross section of an unplanted drying bed and its filter media. When using wheelbarrow and shovel to remove the dried sludge cakes, a ramp is recommended to include in the design.

Drying beds are typically rectangular and constructed out of concrete, bricks or stone masonry. The sides need to be high enough to account for hydraulic loadings. The design includes a splash plate to disrupt flow during loading, and a ramp for solids removal. The filter media usually consists of layers of sand and gravel, increasing in diameter with depth, see Figure 3.3.1 and Table 3.3.1. Treatment capacity is controlled by solids and hydraulic loading rates, and the treatment performance is based on the filter layer separating solids by exclusion.

Table 3.3.1 Recommended layer depth and particle sizes for sand and gravel in unplanted drying beds.

	Layer depth [cm]	Particle size [mm]
Faecal sludge	20 – 30	–
Sand	10 – 20	0.1 – 0.5
Fine Gravel	10	5 – 15
Coarse gravel	15 – 20	20 – 40

Prior to designing unplanted drying beds, Capillary Suction Time (CST) tests and dewaterability (TS following centrifugation) should be carried out to determine the dewaterability of the specific faecal sludge. It has been observed that stabilized faecal sludge dewaters better than faecal sludge with short storage time in containment or with high fats, oils and grease content. However, further research is needed to provide additional understanding. To address this, faecal sludge with different levels of stabilization could be mixed.

The required level of dewatering will depend on the intended enduse. For example, 50% dryness is recommended prior to pelletizing with the Bioburn pelletizer, 90% for use as a dry combustion fuel and 40-60% for co-composting. However, for faecal sludge to be removed from the drying beds, it needs to be spadable (easily removed with a shovel). Usually it takes 10-30 days for faecal sludge to reach 20-50 % TS, depending on the faecal sludge characteristics, loading rates, filter media and climate.

3.3.2 Sizing unplanted drying beds

The approach outlined below for the sizing of unplanted drying beds is summarized in Table 3.3.2.

Table 3.3.2 Step-by-step approach for design of unplanted drying beds.

Step 1	Establish design criteria
Step 2	Determine total drying cycle
Step 3	Calculate surface area
Step 4	Validate surface area
Step 5	Determine number of drying beds
Step 6	Specific concerns with operation and maintenance

Step 1: Establish design criteria

The design of unplanted drying beds is based on the discharged TS concentration and volume. Faecal sludge can be loaded directly onto drying beds or can be loaded from prior technologies such as settling-thickening tanks. Capillary Suction Time (CST) and dewaterability (TS following centrifugation) should be conducted to evaluate the times required for dewatering.

The following parameters are required to calculate the surface area and required numbers of drying beds:

- Q_s : Discharged faecal sludge [m^3/d]
- C_{TS}: Incoming TS concentration [$\frac{kg\ TS}{m^3}$]
- t_{tot} : Total drying cycle [d]
- f_{op}: Delivery/operating days per year [d/yr]
- HLR: Hydraulic loading rate [m/loading]
- SLR: Solids loading rate [$\frac{kg\ TS}{m^2 \cdot yr}$]

Step 2: Determine total drying cycle

The total time required for each drying cycle (t_{tot}), is the sum of the time for loading the faecal sludge onto beds (t_l), drying time (t_d) and the time for dried solids removal (t_{sr}). T_{tot} is affected by climate (e.g. humidity, wind, temperature and rainfall). In areas with heavy rain, roofs can be constructed over drying beds.

t_{tot} : Total drying time [d] t_l: Loading time [d] t_d: Drying time [d] t_{sr}: Faecal sludge removal time [d]	$t_{tot} = t_l + t_d + t_{sr}$

Number of drying cycles per year

After determining the time required for one drying cycle, the number of drying cycles in one year can be determined. Drying cycles per year can be calculated by dividing days per year with drying cycle time.

n: Drying cycles per year [cycles/yr]	$n = \left(\frac{days\ per\ year}{Total\ drying\ time}\right)$

Unplanted drying beds will be loaded and unloaded depending on the different treatment technologies that are used before and after the drying beds. For example, settling-thickening tanks that are manually emptied cannot be discharged on a daily basis, rather on a monthly basis.

Step 3: Calculate surface area

a) Select the loading rate

Area requirements are estimated by either the hydraulic loading rate or solids loading rate. Recommended hydraulic loading rates are 0.2-0.3 m per cycle. Solids loading rates are 50-300 kg TS/m^2.yr in general; however, 100-200 kg TS/m^2.yr is usually recommended in tropical countries.

b) Surface area calculations based on solids loading rate

$\dot{m}_s$: Solids loading $[\frac{\text{kg TS}}{\text{yr}}]$ Q_s: Discharged faecal sludge [m^3/d] C_{TS}: TS concentration of incoming faecal sludge $[\frac{\text{kg TS}}{\text{m}^3}]$ f_{op}: Delivery/operating days per year [d/yr] SA_{SLR}: Surface area based on SLR [m^2] SLR: Solids loading rate $[\frac{\text{kg TS}}{\text{m}^2.yr}]$	*Solids loading*: $\dot{m}_s = Q_s \times C_{TS} \times f_{op}\ \left[\frac{\text{kg TS}}{\text{yr}}\right]$ *Surface area* : $SA_{SLR} = \sum\{\dot{m}_s \div SLR\}$ [m^2]

Step 4: Validate surface area

It is important to validate the calculation, since the largest calculated area will govern the design.

SA_{SLR}: Surface area based on SLR [m^2] SA_{HLR}: Surface area based on HLR [m^2]	$SA = \max(SA_{SLR}, SA_{HLR})$ [m^2]

SA_{HLR}: Surface area based on HLR [m^2] Q_s : Daily inflow of faecal sludge to the drying bed [m^3/d] t_{tot} : Total drying time [d] HLR: Hydraulic loading rate [m/loading]	$SA_{HLR} = Q_s \times t_{tot} \div HLR$ [m^2]

The relationship between hydraulic loading rate and solids loading rate can be used to calculate the actual operating hydraulic loading or solids loading rate based on the governing surface area.

SLR: Solids loading rate $[\frac{\text{kg TS}}{\text{m}^2.yr}]$ HLR: Hydraulic loading rate [m] C_{TS}: TS concentration of incoming faecal sludge $[\frac{\text{kg TS}}{\text{m}^3}]$ n: Drying cycles per year [1/yr]	$\text{SLR} = \text{HLR} \times \text{C}_{\text{TS}} \times \text{n}\ [\frac{\text{kg TS}}{\text{m}^2.yr}]$

Step 5: Determine number of drying beds

To determine number of drying beds, the total drying time, total incoming faecal sludge quantity and its loading frequency on the drying beds need to be considered. However, actual number of beds also include a safety factor, for example, the amount of time or space covering one additional day of operation, and enough beds to not exceed 300 m^2 per bed.

For example, if faecal sludge need to be loaded daily, a simplified assumption of that the number of operating days until next loading can be used as the minimum amount of required beds. With a total drying time of 14 days and if the treatment plant operates six full days per week (Monday through Saturday). Then there are 12 operating days between each loading and 12 drying beds are required plus a safety factor of for example one bed, see Figure 3.3.2. Which will allow for desludging or fluctuating quantities and qualities of the incoming faecal sludge.

Another example, if you have 180 m^3 to load and a hydraulic loading of 30 cm, on a hydraulic loading basis you need 180 m^3 / 0.3 m = 600 m^2 to accommodate that. Since 300 m^2 per bed should not be exceeded, two beds are required.

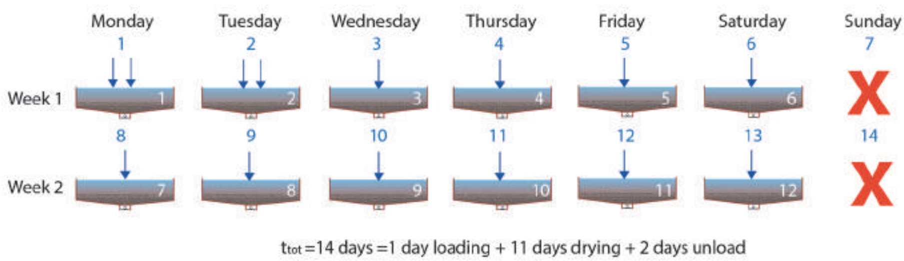


Figure 3.3.2 Illustration that 12 drying beds are required for a total drying cycle of 14 days, if faecal sludge are loaded every day, with 6 days operation at the faecal sludge treatment plant. The same principal can be applied to other drying requirements and operation days at the treatment plant.

Step 6: Specific concerns with operation and maintenance

Operation and maintenance to consider for unplanted drying beds:

- Sand and gravel must be washed prior to placing it in the filter to remove dust particles which could cause clogging of the beds.
- When loading it is very important not to exceed loading rates (hydraulic or solids).
- Faecal sludge can only be loaded onto drying beds once during each drying cycle. Partially dewatered faecal sludge forms a crust on the surface that prevents liquid from passing down to the sand layer and percolating through the drying bed.
- Incorrect loading can lead to ponding or clogging of beds. If clogging occurs, the entire sand and gravel layer needs to be washed or replaced.
- Solids removal is labour intensive, so adequate time needs to be estimated to ensure that loading cycles can be maintained.
- During solids removal, measures need to be taken to minimize the sand loss, as the sand layer is slowly removed, it needs to be replaced.
- As the sand layer is slowly removed, it needs to be replaced.
- Electrical operation and maintenance must be included if pumps are used for loading of the drying beds. Examples are spare parts and fuel.
- It is important to monitor the leachate as an indicator of the drying bed performance (e.g. total volumes, TS concentration).

Example 3.3.1 Sizing of an unplanted drying bed

Determine the required number and size of drying beds for thickened faecal sludge coming from a settling-thickening tank with a sludge TS of 4%. The settling-thickening tank is emptied and loaded to the drying beds every 10 days. The total drying time, of the faecal sludge obtained after a dewaterability test, is 30 days including loading and removal. The treatment plant will be open for discharge six days a week. Additional assumptions include:

- Q_s = 750 m^3 thickened FS/loading
- HLR = 0.3 m/loading
- SLR = 220 kg TS/m^2.yr

Solution:

4 % TS is equivalent to 40 g TS/L thickened faecal sludge, assumed the specific density is close to water.

First determine the number of cycles per year.

Total drying time is 30 days, $n = \left(\frac{\text{days per year}}{\text{drying cycle time}}\right) = \frac{365}{30} = 12 \text{ cycles /yr}$

So every bed can be used 12 times per year.

Since the total drying time is 30 days and the settling-thickening tank is emptied every 10 day, you have 3 loadings per drying cycle.

Determine the surface area required to fulfil incoming loadings per year and the solids loading rate.

$$\dot{m}_s = Q_s \times C_{TS} \times n = 3 \times 750 \text{ (m}^3\text{/cycle)} \times 40 \text{ (kg/m}^3\text{)} \times 12 \text{ (cycles/yr)} = 1{,}080{,}000 \text{ kg TS/yr}$$

$$SA_{SLR} = \frac{\dot{m}_s}{SLR} = \frac{1{,}080{,}000 \text{ kg TS/yr}}{220 \frac{\text{kg TS}}{m^2.\text{yr}}} = 4{,}909 \text{ m}^2$$

Validate the surface area based on the solids loading rate with the hydraulic loading rate

$$SA_{HLR} = \frac{Q_s}{HLR} = \frac{3 \times 750\left(\frac{\text{m}^3}{\text{loading}}\right)}{0.3\left(\frac{\text{m}}{\text{loading}}\right)} = 7{,}500 \text{ m}^2$$

To have adequate area for treatment the maximum area of the two calculations based on hydraulic and solids loading is the limiting factor.

$$SA = \max(SA_{SLR}, SA_{HLR}) = SA_{HLR} = 7{,}500 \text{ m}^2$$

Calculate the operating solids loading rate

$SLR = HLR \times C_{TS} \times n$ = 0.3 (m/cycle) × 40 (kg TS/m^3) × 12 (cycles/yr) = 144 kg TS/m^2.yr

Calculate the number of drying beds

Knowing that you have 750 × 3 = 2,250 m^3 incoming faecal sludge, a rule of thumb with maximum 300 m^2 per drying bed and, a hydraulic loading rate of 0.3 m. The final number of drying beds are

$$\frac{\frac{750\times3\,\frac{m^3}{cycle}}{0.3\ m}}{300\ m^2} = 25 \text{ drying beds}$$

A minimum of 25 beds, each 300 m^2, are required to treat the thickened faecal sludge discharged from the settling-thickening tank. Resulting in an operational hydraulic loading rate of 0.3 m per load and solids loading rate of 144 kg/m^2.yr.

Case study 3.3.1 The reality of the design process in FSM

Provided by CDD (Consortium for DEWATS Dissemination) Society

The Devanahalli faecal sludge treatment plant designed by CDD Society India includes 10 unplanted drying beds. 200 kg TS/m^2.yr was used as the solids loading rate to design 128 m^2 drying beds for a treatment capacity of 6 m^3 per day. After validating the loadings, the hydraulic loading was adjusted to 25 cm to reduce the required number of beds. Due to climatic factors such as higher humidity and lack of sufficient sunlight, it took 30 days to dry to the desired dryness of 30-50%, instead of the design value of 15 days. However, when the treatment plant opened, there were fewer trucks discharging than expected. This allowed time to research and put into place measures to increase the dewatering capacity.

Consequently, the hydraulic loading was decreased from 25 cm to 20 cm, also reducing the solids loading to 185 kg TS/m^2.yr. Greenhouse roofs with exhaust fans were constructed over the beds. As a last attempt, paths were made in sludge cakes by shovels to expose the full sludge cake profile to heat and sunlight, see Figure 3.3.3.

Figure 3.3.3 Pathways created in the sludge cake to increase exposure to heat and sunlight.

Another problem that was addressed was that during removal of the sludge cakes from the drying beds, 5 cm sand in two years was also removed from the beds. Sand particle size was increased and the beds were covered with Mangalore tiles to prevent sand loss, see Figure 3.3.4. The increased particle size also decreased drying times. Consequently, the design parameters were modified according to the new operating conditions, and the plant can now operate at the design loading rates.

Figure 3.3.4 Mangalore tiles and their arrangement prior addition of the sand layer.

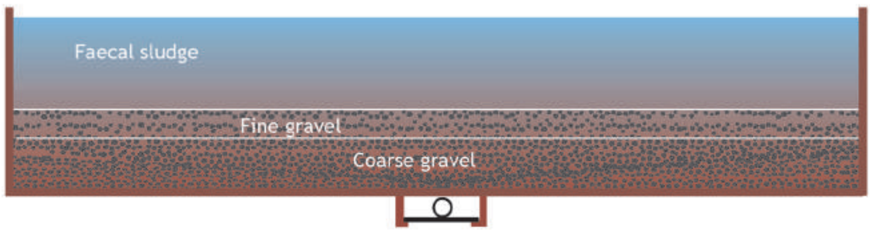
Table 3.3.3 Final operating design parameters for Devanahalli faecal sludge treatment plant.

Parameters	Unit	Values
Estimated discharge volume	m^3 /loading	2.5
Solids loading rate	kg TS/m^2.yr	185
Total number of beds	no.	10
Hydraulic loading rate	m/loading	0.2
Size of each bed	m^2	5.8 × 2.1
Total area required	m^2	128
Feeding frequency	days	Alternative days
Drying period	days	15-20

Exercises

1. Describe three differences between planted and unplanted drying beds.
2. What are and are not the treatment objectives of unplanted drying beds? Explain.
3. When designing unplanted drying beds there is a trade-off between solid-liquid separation performance, available land space, and total solids concentration of the faecal sludge. Name three conditions in which unplanted drying beds are NOT optimal.
4. The purpose of dewatering is to separate solids and liquids in the faecal sludge. Drying can then, for example, be achieved by evaporation. Explain and describe where each mechanism (dewatering, drying and evaporation) occurs during the treatment process with unplanted drying beds
5. Drying beds can follow settling-thickening tanks in a treatment chain. Which four parameters do you need to know about the design and characteristics of the settling-thickening tank to design drying beds?
6. Explain how dewatered faecal sludge is removed from unplanted drying beds, and list all the equipment required during the operation, including safety equipment.
7. What infrastructure is recommended for easy removal of dried solids from unplanted drying beds, and is frequently neglected?
8. The filter media in unplanted drying beds typically consists of layers of sand and gravel, which increase in particle size from top to bottom. What are the maintenance issues specific to the filter media? Which design consideration increases the likelihood of appropriate maintenance of the filter media?
9. If no leachate is flowing from the drainage system of a drying bed what could be the cause? What steps should the plant operator take?
10. Prior to designing unplanted drying beds, which site-specific parameters should be evaluated in a laboratory?

11. What three features are missing from this schematic, and what consequences will this have?



12. What are three positive and three negative aspects for the usage of volume or kg Total Solids when discussing capacity for faecal sludge treatment plants? Include terms such as faecal sludge variability, emptying, adequate treatment and transportation.
13. Climates with high ambient temperature and low relative humidity are optimal for drying. In climates with frequent rainfall, dewatering and drying times can be prolonged. In rainy climates, a cover over the drying beds should be considered. Name four design parameters for adequate roofing of unplanted drying beds.
14. Even if it is highly recommended not to, operators could still be tempted to increase hydraulic loading rates to temporarily increase the amount of faecal sludge that can be loaded onto drying beds. How do different hydraulic loading rates influence total drying time?
15. Faecal sludge from onsite containment that is emptied frequently is less stable than faecal sludge that has been stored for years. How is the treatment performance of unplanted drying beds likely to change with an increase of unstable faecal sludge coming in? What steps can be taken to ensure system performance?

Design and calculate

16. Sizing of unplanted drying beds should be based on the faecal sludge origin and its TS; drying beds are commonly loaded with faecal sludge from several technologies. However, it is preferable to have separately allocated drying beds for the settling-thickening faecal sludge and the faecal sludge emptied from stabilization ponds. During the rainy season the drying time is 30 days, while in the hotter/dry season it is only 15 days. The treatment plant typically operates 6 days a week.
<u>Settling-thickening tank output data</u>
40 m^3/day
40 g TS/L FS
<u>Stabilization pond output data</u>
0.8 m^3 of wet faecal sludge/day
18 kg TS/day
    a) Draw a process flow for a typical treatment system including screening, settling-thickening tank, drying beds and waste stabilization ponds.
    b) How much surface area is required for adequate treatment to fulfil a solid loading rate of 250 kg TS/m^2.yr or a 30 cm hydraulic loading?
    c) How many drying beds are needed to support the operation?

17. What is the drying bed surface area that is required for loading of 1,584m^3 faecal sludge per drying cycle from a settling-thickening tank? Assume a hydraulic loading rate of 0.3 m and a solids loading rate of 300 kg TS per square meter and year, and that the incoming faecal sludge has a concentration of 80 kg TS/m^3.

18. Two engineers are discussing required surface area to treat a daily flow of 20 m^3 faecal sludge/day with a TS concentration of 45 g TS/L. The first one states that you need 1,667 m^2 while the other argues for 1,404 m^2. Both of them assume a hydraulic loading rate of 0.3 m/loading, solid loading rate of 200 kg TS/m^2.yr and a total drying cycle of 25 days. The faecal sludge treatment plant is assumed to be open 6 days a week. Determine who is right and discuss why one of them is wrong.

19. How does the total solids concentration of faecal sludge affect the required drying bed surface area? When should the design be governed by:
    a) solids loading rate?
    b) hydraulic loading rate?

    Do two calculations and illustrate your answers based on 12,000 mg TS/L and 100,000 mg TS/L; all other assumptions should be the same.

20. Two engineers are discussing the surface area required to treat a daily flow of 20 m^3 faecal sludge/day with a TS concentration of 45 g TS/L. The first engineer says that you need 1,667 m^2 while the other argues for 1,404 m^2. Both of them assume a hydraulic loading rate of 0.3 m/loading, solid loading rate of 200 kg TS/m^2.yr and a total drying cycle of 25 days. The faecal sludge treatment plant is assumed to be open 6 days a week. Determine who is right and discuss why one of them is wrong.

21. Available land is a common challenge for urban faecal sludge treatment plants.
    a) You are asked to evaluate the number of drying beds required to treat incoming faecal sludge based on total drying times. Assume 8 days' drying time, that one bed per day is loaded, and operation is 5 days a week. Make time assumptions for the loading and unloading time.
    b) After your first estimate, you discover that it needs to be increased by 3 days' total drying time to account for removal of dewatered faecal sludge. How do your assumptions change when you take this into account?

22. Calculate the required number of beds based on the surface area, with the following assumptions:
    - Q_s = 20 m^3/day
    - C_{TS} = 50 g TS/L
    - HLR = 0.2m
    - SLR = 300 kg TS/m^2.yr

Technology

Chapter 3.4

Planted drying beds

Miriam Englund and Linda Strande

Learning objectives

- Explain the treatment process and operation
- Discuss the operation and maintenance requirements
- Name the design parameters

Textbook

Available at www.sandec.ch/fsm_book

- Kengne, I. M., & Tilley, E. (2014). Planted drying beds. In Strande, L., Ronteltap, M., and D. Brdjanovic (Eds.) *Faecal Sludge Management: Systems Approach for Implementation and Operation*.

Free online course (MOOC)

Available at www.eawag.ch/mooc

- *Introduction to Faecal Sludge Management*. MOOC series by Eawag and EPFL. Module ´Planted Drying Beds´.

Further Eawag-Sandec publications

Available at www.sandec.ch/fsm_tools

- Gueye, A., Mbeguere, M., Niang, S., Diop, C. and Strande, L. (2016). *Novel plant species for faecal sludge drying beds: Survival, biomass response and forage quality.* Ecological Engineering. 94, 617-621.
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Additional resources

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- Joceline, S.B., Koné, M., Yacouba, O. and Arsène, Y.H. (2016). *Planted sludge drying beds in treatment of faecal sludge from Ouagadougou: Case of two local plant species*. Journal of Water Resource and Protection 8(07): 697.
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Introduction

Planted drying beds are used to dewater and stabilize faecal sludge. They are similar to unplanted drying beds in that they both consist of a gravel and sand filter bed, and are designed based on hydraulic and solids loading rates. Faecal sludge is loaded onto the top and the leachate percolates through the bed and is drained away in an underdrain. The difference between planted and unplanted drying beds is that in planted drying beds, the filter bed is used for growing plants and is fed continuously with faecal sludge, whereas unplanted drying beds are batch operated. Planted drying beds are loaded 1 – 3 times a week, with a hydraulic loading rate of 7.5 – 20 cm of sludge per loading depending on the context. For practical reasons, thinner layers are more difficult to evenly distribute.

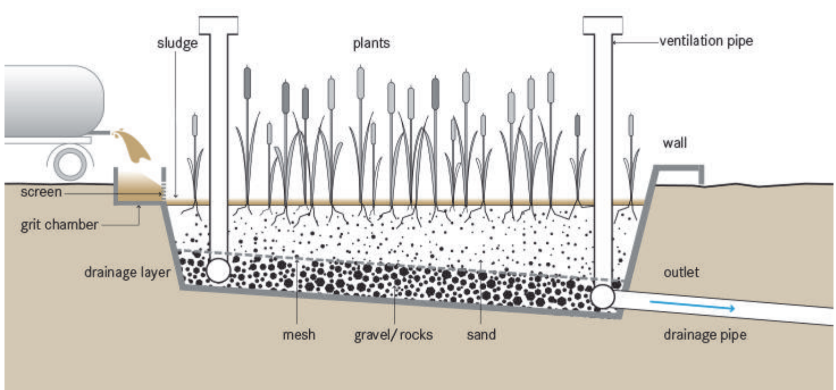

Figure 3.4.1 Schematics of a suggested layout of a planted drying bed (Tilley *et al.,* 2014).

As shown in Figure 3.4.1, the planted drying bed is preceded by a grit chamber so that the incoming sludge does not disrupt the filter media and evenly discharges faecal sludge; a screen separates solid waste. Ventilation pipes ensure a constant air flow through the media, though the plant roots and stems form micro-channels which also aid in ventilation. The sidewalls should be high enough to contain the total volumes of loaded sludge, generally recommended to be 1.5 – 2 meters, and the drain should slope towards the outlet; the beds can be loaded for 5 – 10 years with a few months resting prior to desludging. The size of the beds will depend on the topography of the site. For further recommendations on design considerations, refer to Table 8.3 in *Faecal Sludge Management - Systems Approach for Implementation and Operation (2014).*

Table 3.4.1 Filter layer thickness and particle size (Strande *et al.,* 2014).

Filter layer	Thickness [cm]	Particle size [mm]
Sand	10 – 15	10 – 40
Fine gravel	20 – 25	5 – 10
Coarse gravel	20 – 45	0.2 – 0.6

The plants help to facilitate dewatering and the stabilization of organic matter and nutrients of faecal sludge. They keep the bed from clogging and provide a more complex environment for the growth of bacteria within the bed. For the treatment process to be successful, the plants need to survive which means they must be tolerant of fluctuating water levels and salinity, be fast-growing, have high transpiration rates, have deep-growing rhizomes and roots, and be non-invasive. It is crucial that the acclimatization period is long enough to establish plant growth and allow adaption to hostile faecal sludge conditions.

Plant species should be selected based on the local conditions and the resource recovery objectives. For example, from research in Senegal, *E. crus-galli* had optimal growth at loading rates of 200 and 300 kg TS/m^2.yr, whereas *P. geminatum* and *P. vaginatum* had growth at 100 and 200 kg TS/m^2.yr, but both species of plants could be used as animal fodder (Mbeguere *et al.,* 2016). For more examples from Thailand, Cameroon and Senegal, refer to *Faecal Sludge Management - Systems Approach for Implementation and Operation* (2014).

Sizing planted drying beds

The approach outlined below for the sizing of unplanted drying beds is summarized in Table 3.4.2.

Table 3.4.2 Step-by-step approach for the design of planted drying beds.

Step 1	Establish design criteria
Step 2	Calculate surface area
Step 3	Determine number of beds
Step 4	Validate surface area calculations
Step 5	Establish acclimatization conditions
Step 6	Operation and maintenance

Step 1: Establish design criteria

The design of planted drying beds depends on solids loading, feeding frequency, resting periods, plant density, plant acclimatization and plant harvesting. Faecal sludge can be loaded directly onto drying beds or can be loaded using other technologies such as settling-thickening tanks. To determine influent values, the Quantity and Quality (Q&Q) methodology should be used. See list below for input parameters to the design of planted drying beds.

- Q_s : Daily inflow of faecal sludge [m^3/d]
- C_{TS}: Average TS concentration of influent sludge [kg TS/m^3]
- f_{op}: Delivery/operating days per year [d/yr]
- SLR: Solids Loading Rate [kg TS/m^2.yr], typically 100 – 300 kg TS/m^2.yr
- HLR: Hydraulic loading [m/loading], typically 0.075 – 0.2 m per loading.

Step 2: Calculate surface area

Calculate the surface area based on the SLR.

$\dot{m}_s$: Solids loading [kg TS] Q_s : Daily inflow of faecal sludge to the planted drying bed [m^3/d] C_{TS}: Average TS concentration of incoming sludge [kg TS/m^3] f_{op}: Operating days per year [d/yr] SA_{SLR}: Surface area based on SLR [m^2] SLR: Solids Loading Rate [kg TS/m^2.yr]	$\dot{m}_s = Q_s \times C_{TS} \times f_{op}$ [kg TS] $SA_{SLR} = \sum\{\dot{m}_s \div SLR\}$ [m^2]

Step 3: Determine number of beds

The number of beds will depend on the loading frequency of each bed, e.g. 1-3 times a week depending on climate (Sonko *et al.,* 2014) and the frequency and volumes of sludge delivery. There is not a standard size for planted drying beds, but for operational purposes they should not exceed 300 m^2. Multiple beds in parallel are recommended to enable sequential loading and allow a resting phase.

n_{db}: Number of drying beds [bed] f_{op}: Operating days [d/w] f_{load}: Loading frequency [d/w.bed]	$n_{db} = \frac{f_{op}}{f_{load}}$ [bed]

Step 4: Validate surface area calculations

The design was based on SLR, but each time the beds are loaded the hydraulic loading should be within the range of 7.5 – 20 cm. It now needs to be verified that the SLR and HLR can both be met. Otherwise, the largest surface area will govern the design.

HLR: Hydraulic loading [m/loading] Q_s: Daily inflow of FS to the planted drying bed [m^3/d] A_{db}: Area for one drying bed [m^2] $SA_{SLR/HLR}$: Surface area based on either SLR or HLR [m^2]	$HLR = \frac{Q_s}{SA_{SLR}}$ [m/loading] $A_{db} = \frac{SA_{SLR/HLR}}{n_{db}}$ [m^2]

Step 5: Establish acclimatization conditions

The acclimatization phase takes, on average, six months, and in arid climates it should start during the rainy season for best growth. One way to acclimatize the bed is to gradually increase the solid loadings from 50 kg TS/m^2.yr to 200 kg TS/m^2.yr, with a feeding frequency of at least twice a week. Another way would be starting out with dilute wastewater or settling-thickening tank effluent, and gradually moving to full strength faecal sludge. Visual indicators of plant stress such as a yellowish colour or slow growth rates should be carefully observed during this period.

Step 6: Operation and maintenance

The following list presents key considerations for operation and maintenance of planted drying beds.

- It is important to have trained operators who operate and maintain the drying beds, especially during the acclimation period.
- During loading make sure the faecal sludge is well distributed, especially during the start-up to ensure the filter media is not disturbed.
- Plant survival is crucial for treatment performance.
- During the start-up, the solids loading rates and feeding intervals need to be further evaluated to ensure adequate frequencies and loadings for plant health.
- Optimal plant densities and harvesting frequencies should be evaluated.
- Harvest plants by cutting them at the surface; avoid pulling them out because this will damage the root system and drying bed filter material.
- Monitor the drainage system and effluent for treatment performance and any possible changes.
- Remember that wildlife might be attracted to the plants, so fencing and measures to decrease possible vector-borne diseases might be required.

Example 3.4.1 Sizing planted drying beds

Determine the required surface area to treat incoming faecal sludge with the plant *Typha augustifolia*, operated with a solid loading rate of 250 kg TS/m^2.yr, and loaded twice a week. Additional assumptions include:

Estimated faecal sludge reaching treatment plant:	75 m^3 FS/d
TS concentration:	30,000 mg/L
Treatment plant opening hours:	6 days a week

Solution:

Determine the surface area required, given the quantity of incoming sludge and the solid loading rate tolerated by the plant *Typha augustifolia*.

$\dot{m}_s = Q_s \times C_{TS} \times f_{op}$ = 75 [m^3 FS/d] × 30 [kg/m^3 FS] × (6[d/w] × 52[w/year]) = 720,000 kg TS/yr

$SA_{SLR} = \frac{\dot{m}_s}{SLR}$ = 720,000[kg TS/yr] / 250 [kg TS/m^2.yr] = 2,808 m^2

Determine the number of beds required to operate and maintain the planted drying beds.

$n_{db} = \frac{f_{op}}{f_{load}}$ = 6/2 =3 beds minimum < 2,808/300 = 9.36 beds ~ 10 beds.

Since the maximum area per bed is 300 m^2, the number of beds, including a safety factor results in 10. We will load 3 beds per day.

Validate that the hydraulic loading for each application is within the range 7.5 – 20 cm/loading.

$HLR = \frac{Q_S}{SA_{SLR}}$ = 75 [m^3 FS/d] / (3 × 300)[m^2]= 0.08 m/d

We need 10 beds, 2,808 m^2 and a hydraulic loading rate of 8 cm to treat the volume of daily incoming faecal sludge.

Exercises

1. What are the treatment objectives of planted drying beds? Explain them.
2. Explain the mechanisms of the dewatering process in planted drying beds.
3. One possible operational problem that can occur with planted drying beds is ponding due to the faecal sludge forming a crust on the surface when drying. Explain how this can be managed.
4. How can effluent from planted drying beds be further treated? Is this needed?
5. Give five characteristics that plants used in drying beds should have.
6. The planted drying bed has three operational stages in its operational cycle.
   a) Draw a process flow of the planted drying bed operational cycle and the estimated time for each phase.
   b) Explain the appropriate operation during the first phase.
7. One treatment objective for planted drying beds is stabilization of the faecal sludge. When and how does that happen? And how can you account for that in your design?
8. Sludge loading rates can be based on hydraulic loadings or the amount of total solids. What do you need to know in order to calculate the required surface area based on solids loading rates?
9. As head engineer at a faecal sludge treatment plant you get a call from your plant operator saying that your plants have started to wither. What could be the possible reasons, and what is your plan of action?

10. You have just designed a new faecal sludge treatment plant and finished the infrastructure for your planted drying beds. Describe step by step how you will initiate the treatment technology.

11. A festival is coming to town in 4 weeks, and the population in the city is expected to increase by 150% for 2 months. You are in charge of the faecal sludge treatment plant in the area and decide to triple the capacity of the planted drying beds by constructing new planted drying beds. Is this a good idea or not, and why?

12. An existing faecal sludge treatment plant uses planted drying beds with a faecal sludge accumulation rate of 50 – 70 cm per year. Determine how high the freeboard needs to be if desludging happens every fifth year.

13. You are designing a faecal sludge treatment plant and the client wants to know the required surface area. The treatment plant has an influent faecal sludge TS of 30 kg TS/m^3, operates 6 days a week and receives 50 m^3 faecal sludge a day. *Typha Augustifolia* is suggested and can be operated with a solids loading rate of 250 kg TS/m^2.yr and the hydraulic loading rate is suitable as 7.5 – 15 cm with a loading frequency of twice a week.

14. You are evaluating new plant species for your large-scale planted drying bed. For one of the plants species, trials from other cities recommend a loading frequency of 1 – 3 times a week. Use operational data of 40 m^3 faecal sludge a week and per bed, and assume that each bed has an area of 250 m^2.
    a) Calculate loading depths for different loading frequencies (1, 2, 3 times a week).
    b) What other parameters apart from hydraulic loading will influence the planted drying bed?

15. In urban areas there is always limited land available for construction of faecal sludge treatment plants. There is 8,000 m^2 available for planted drying beds; will that be enough for treatment of faecal sludge from the city of Duckholm? Assume a solids loading rate of 200 kg TS/m^2.yr.

    Duckholm
    Population: 1,250,000
    Faecal sludge produced: 62 m^3 /cap.yr
    Wastewater connection: 20%
    Accumulated faecal sludge: 70 L/cap.yr
    TS concentration: 30 kg TS/m^3 FS

16. Your sanitary process engineer shows you calculations and size estimations for a future planted drying bed. What went wrong?

$$SA_{SLR} = \frac{\dot{m}_s}{SLR} = \left(\frac{C_{TS1} + C_{TS2}}{2}\right) \times (\dot{Q}_1 + \dot{Q}_2) \times f_{op}$$

Chapter 3.5

Co-composting

Miriam Englund and Linda Strande

Learning objectives

- Explain the treatment process and operation
- Discuss the operation and maintenance requirements
- Name the design parameters

Textbook

Available at www.sandec.ch/fsm_book

- Strande, L., Ronteltap, M., and D. Brdjanovic (Eds.) *Faecal Sludge Management: Systems Approach for Implementation and Operation*.

Free online courses (MOOCs)

Available at www.eawag.ch/mooc

- *Introduction to Faecal Sludge Management.* MOOC series by Eawag and EPFL. Module ´Co-composting´.
- *Municipal Solid Waste Management in Developing Countries.* MOOC series by Eawag and EPFL. Week ´Organic waste treatment´.

Further Eawag-Sandec publications

Available at www.sandec.ch/fsm_tools

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Additional resources

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Introduction

Composting is the controlled decomposition of organic material into biologically stable humic substances, carried out by microorganisms and invertebrates in the presence of oxygen. The compost that is finally produced is stable, does not degrade further and is an excellent soil amendment that can improve soil structure and provide nutrients. The need for co-composting faecal sludge with another organic substrate is due to both the low carbon to nitrogen (C:N) ratio in faecal sludge and its high liquid content. If the co-composting process is operated appropriately, treatment objectives such as pathogen reduction, nutrient management, and stabilization can all be achieved. The treatment objectives are fulfilled by regulating the moisture content (~65%), C:N ratio, aeration and temperature. Furthermore, co-composting can reduce around 50% of the volume entering the heap.

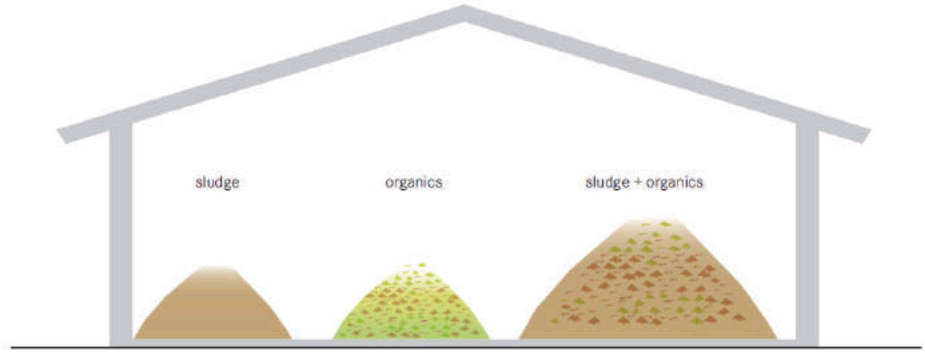


Figure 3.5.1 **Overview of co-compost as a treatment technology (taken from the MOOC '*Municipal Solid Waste in Developing Countries*').**

The input material for composting needs to have a C:N ratio between 20:1 and 35:1, so it is necessary to mix faecal sludge with carbon-rich organic matter, and it also needs to have a moisture content of 50-60 %; typically dewatered faecal sludge reaches 30-50 % and a C:N ratio of 18.22±11.12. Therefore, it is recommended to mix faecal sludge in a 1:2-10 ratio with other organic waste. For example, in Ghana, the faecal sludge that IWMI is working with is 93-99% water, and following dewatering with drying beds, the dried faecal sludge has a C:N ratio of 11±3 (Cofie *et al.* 2016).

Pathogen inactivation during co-composting is achieved by thermophilic conditions over a period of time. Monitoring and maintaining the operating parameters as designed is important to achieve this. If the composting process is not properly maintained, pathogen inactivation could also occur due to storage time in the heap, but this is not reliable and should not be designed for. The key point is that, in reality, the mixing, moisture content and storage are all arbitrary, and the outcome is difficult to control. Local operators usually gain their own knowledge about how the pile should be operated in order not to overheat. Three composting technologies are: 1) windrow; 2) aerated static; and 3) in-vessel. Solid waste such as plastic will not decompose and should be removed prior to co-composting.

Sizing co-composting treatment

The approach taken here for the sizing of co-composting is summarized in Table 3.5.1.

Table 3.5.1 **Step-by-step approach for the design of co-composting with faecal sludge.**

Step 1	Establish design criteria
Step 2	Determine required mass of bulk material
Step 3	Determine C:N ratio and moisture content
Step 4	Calculate area requirements
Step 5	Calculate pathogen inactivation
Step 6	Operation and maintenance

Step 1: Establish design criteria

Presented in Table 3.5.2 are the operation and design recommendations for co-composting. It is important not to be overly influenced by these numbers but to understand how the parameters function and how they relate to each other. In reality there is a lot of trial and error needed in order to reach the correct operational parameters for each local context.

Table 3.5.2 Collection of recommended ranges for parameters displayed in the table. (Cofie *et al.,* 2016; Strande *et al.,* 2014; Tilley *et al.*, 2014)

Parameter	Range in literature
Temp [°C]	>50
Moisture content [weight %]	50-60
Turning frequency [-]	3-6 turnings per 3 months
Pile size (Width : Height : Length) [m]	2 : 1.6 : Length
Faecal sludge : organic solid waste	1 : 2-3
Particle size [cm]	1-2.5 cm forced aeration systems 5-10 cm passive aeration <5 cm static piles
C : N ratio in pile	20-35 : 1
Co-compost cycle [weeks]	6-12

To start the design of co-composting, establish the C:N ratio and moisture content of the feedstock. In reality, it will be adjusted and fine-tuned during the operation, but it is important to consider both the availability of materials and the inter-relation of the operating parameters. Listed in Table 3.5.3 are types of organic waste that you could use for co-composting, depending on their availability, cost and qualities (e.g. moisture, C:N, and particle size). These qualities will also affect the composting times required to achieve stabilization.

Table 3.5.3 Types of organic waste that can be co-composted with faecal sludge and where they can be found. (Cofie *et al.*, 2016)

Source of material	Type of waste
Residences and gardens	Garden trimmings, leaves, grass cuttings
Restaurants and canteens	Raw peelings and stems, rotten fruit, vegetables and leftover food
Market	Organic waste of vegetable and fruit markets
Agro-industries	Food waste, bagasse, organic residues
Parks	Grass clippings, twigs and branches, leaves
Municipal areas	Residential solid waste, human and animal excreta
Dumping sites	Decomposed waste
Animal excreta	Cattle, poultry, pig dung from urban and peri-urban farms
Slaughterhouses	Contents of the digestive system

Examples of ranges of C:N ratios are provided in Table 3.5.4; for more input material refer to databases such as Phyllis2.

Table 3.5.4 Typical characteristics of co-composting input material in Ghana. 1) Cofie *et al.,* 2009; 2) Phyllis2, 2018; 3) Brady and Weil, 2002.

Input material	MC [wt %]	% c_n	% n_n	C:N
Dewatered faecal sludge(1)	42.3±0.42	11.39±7.7	1.05±1.02	18.22±11.12
Household waste(1)	50.65±0.92	30.2±14.9	1.43±0.33	31.44±6.93
Municipal organic waste(1)	68.05±1.34	32.81±19.08	1.25±0.93	28.49±6.00
Sawdust(2)	8	46.8	0.11	425.45
Newspaper(3)				120
Sugarcane waste(3)				50

Step 2: Determine required mass of bulk material

The mass of each input material will affect both the moisture content and C:N ratio; the process to find the optimum is iterative. To adjust the moisture content in the co-compost heap to a range between 40-60 %, the faecal sludge needs to be mixed with a bulk material with compatible moisture content. The following equation can be used to calculate the required mass of bulk material:

MC_n: Moisture content of n [weight %]
m_n: Mass of organic material n [kg]

$$m_1 = \frac{m_{FS}(MC_{FS} - MC_{mix})}{MC_{mix} - MC_1} \text{ [kg]}$$

The same equation can be used to extract moisture contents if the mass of both materials is known. The required volume of each input material is calculated using the density of the bulk agent and calculated mass.

Step 3: Determine C:N ratio and moisture content

The moisture content and C:N ratio are design variables that are interrelated with the input material mass. To determine the C:N ratio of the mixed pile, Table 3.5.4 or databases such as Phyllis2 can be used as a template to collect information similar to the specific context. This can then be solved for example with any solver data software such as Excel to iteratively find a C:N ratio between 20:1 and 35:1 and moisture content of 40-65 % for your pile and, as Step 2 mentions, what mass is required.

$C:N_{mix}$: C:N ratio of co-compost mix [-]
c_n: Carbon content (%) of material n [%]
n_n: Nitrogen content (%) of material n [%]
m_n: Mass of organic material n [kg]
MC_n: Moisture content of n [weight %]

$$C:N_{mix} = \frac{m_1 \times c_1(100 - MC_1) + m_{FS} \times c_{FS}(100 - MC_{FS}) + .. + m_n \times c_n(100 - MC_n)}{m_1 \times n_1(100 - MC_1) + m_{FS} \times n_{FS}(100 - MC_{FS}) + .. + m_n \times n_n(100 - MC_n)}$$

Step 4: Calculate area requirements

Depending on whether mechanical or manual turning is used, differently sized piles are practical. Piles higher than 1.6 m and wider than 2 m should be avoided. With mechanical turning, other sizes are possible. The total surface area required includes space for the heaps and storage of input material and finished product.

SA: Surface area [m^2]	$SA = SA_{Co-compost} + SA_{Storage}$ [m^2]

As seen in Figure 3.5.1, the co-compost can be roofed to protect from rain and other unfavourable weather conditions. Extreme humid conditions might require more than roofing in order to keep it to a maximum of 60 %, such as walls, additional coverage of the pile, fans and improved drainage. Additionally the flooring should be lined and drainage in place, if needed.

Step 5: Calculate pathogen inactivation

Pathogen inactivation can occur as a result of the heat that is generated during the active phase of the composting process; the full process takes up to 90 days. Based on the review of field data compiled by Feachem *et al.* (1983), Vinnerås *et al.* (2003) derived equations to predict the relationship between composting temperature and time required for total removal of viable Ascaris. The equation for Ascaris is:

t: Total removal time [d] T: Co-compost temperature [°C]	$t = 177 \times 10 - 0.1922(T - 45)$ [d]

When depending on pathogen inactivation, temperatures need to be adequately measured to ensure thermophilic temperatures during the full period of time.

Step 6: Operation and maintenance

Co-composting needs to be monitored continuously in order to ensure adequate temperature and moisture content to achieve the treatment objectives. In addition, specific operational and maintenance concerns include:

- When turning the pile, all parts must be exposed to a high temperature in order to kill off the pathogens.
- The temperature is regulated by turning the pile more often if the temperature is too high. If too low, more water potentially needs to be added and/or the mass of moist input material needs to be increased.
- The aerobic condition in the pile is facilitated by the heap-turning frequency, which is context-dependent and needs to be determined by trial and error.
- Mycelium (clumps of white threads) and small insects are present to break down complex organic material and particles.
- Odour problems can be a sign of too high a moisture content and can be reduced by increased turning and the addition of coarse material.
- It may be necessary to cover co-compost piles to either protect from, or to maintain, humidity.

- Large amounts of flies, insects and rodents must be avoided. Covering the pile could reduce the number of flies, insects and rodents gathering.
- Compost as a product is sieved to separate coarse and fine compost. The coarse compost is reused in the next round of co-composting while the fine compost is ready to be used as a soil amendment.

Example 3.5.1

You have 30,000 kg dewatered faecal sludge per pile; how can a C:N ratio of 25:1 and a moisture content of 50% be achieved in a co-compost with a mixture of market waste and faecal sludge with the following characteristics?

	N [%]	C [%]	m [kg]	MC [%]
Faecal sludge	1.5	15	30,000	50
Market waste	1.5	40	?	65

a) Calculate the required mass of market waste to obtain a 25:1 ratio.
b) Calculate the operating ratio between faecal sludge : market waste and compare it with the recommended 1:3.
c) Calculate the moisture content for the mixture and compare to the recommended 40-60 % range.

Solution

$$a)\ C:N_{mix} = \frac{\mathrm{m_{MW}} \times c_{MW}(100 - \mathrm{MC_1}) + \mathrm{m_{FS}} \times c_{FS}(100 - \mathrm{MC_{FS}})}{\mathrm{m_{MW}} \times n_{MW}(100 - \mathrm{MC_1}) + \mathrm{m_{FS}} \times n_{FS}(100 - \mathrm{MC_{FS}})} =$$

$$25 = \frac{(\mathrm{m_{MW}} \times 0.4 \times (100 - 65) + 30{,}000 \times 0.15 \times (100 - 50)}{(\mathrm{m_{MW}} \times 0.015 \times (100 - 65) + 30{,}000 \times 0.015 \times (100 - 50)}$$

$\rightarrow \mathrm{m_{MW}} \sim 385,714$ kg market waste

Carbon and nitrogen values are obtained through testing; the mass of each input can be changed to obtain the targeted C:N ratio of the co-compost.

b) We assume that the 30,000 kg FS is per co-compost cycle.

$$\frac{385{,}714\ [\text{kg MW}]}{30{,}000\ [\text{kg FS}]} = 12.9$$

1:12.9 is higher than the recommended rate (1:3) and more faecal sludge could be added.

c) $\mathrm{MC_{mix}} = \frac{(30{,}000 \times 0.50) + (385{,}714 \times 0.65)}{(30{,}000 + 385{,}714)}$ = 64% moisture content which is slightly over the recommended range.

Options to reduce the moisture content include 1) reduce the market waste volume, and 2) increase aeration or further dry the input material. High moisture levels increase the risk of anaerobic conditions and therefore they need to be prevented.

Exercises

1. Co-composting and composting are established technologies to produce soil amendment. Co-composting is an established faecal sludge treatment technology, but why is it more favourable to co-treat faecal sludge than compost it independently?
2. What is/are the treatment objective(s) of co-composting?
3. Name the three most relevant operational parameters for co-composting with faecal sludge and explain why they are relevant.
4. Prior dewatering is required in order for the faecal sludge to be suitable as an input material for the co-compost. Both the ambient temperature and the temperature inside the composting pile impacts the operating moisture content.
   a) What is the main reason for the dewatering step prior to co-composting?
   b) Discuss different options on how to regulate temperature inside a co-compost pile.
5. How does the particle size of dewatered faecal sludge, the organic matter, and the oxygen concentrations in the co-compost affect performance? Write one sentence each.
6. The co-composting cycle has three phases: the active stage/thermophilic, cooling stage/ transformation and maturation stage. Why is it important that the co-compost has matured before applying on soil?
7. Pathogen inactivation is one of the treatment objectives when designing for co-compost. Most often Ascaris eggs are used as an indicator for whether the faecal sludge is adequately treated or not; why?
8. Name two advantages and two disadvantages for each of the three different compost technologies: aerated static piles, windrow composting and in-vessel composting.
9. Why is it normally not possible to compost faecal sludge without a co-feedstock?
10. Explain with a graph how pH and temperature change over time during the co-composting lifecycle. What happens to the pathogen inactivation if temperature increases?
11. Moisture content, temperature and C:N ratio are the most important design parameters for co-composting. Name three design variables that affect the output of the co-compost.
12. One argument against co-composting with faecal sludge is that you decrease the performance of the full composting process. Give three advantages of co-composting with faecal sludge compared to other input materials.
13. Discuss why it is important to consider C:N ratios and moisture content together.
14. Composting can be used to treat faecal sludge and other wastewater-derived solids and to produce a product suitable for use as a soil amendment. If the ambient temperature is 20°C, and we measure a compost temperature of
    a) 50°C
    b) 60°C.
    How many days are required to ensure the composted material is pathogen-free?

15. With 50,000 kg faecal sludge per pile, how can a C:N ratio of 30:1 and a moisture content of 50 % be achieved in a co-compost with a mixture of market waste and faecal sludge with the following characteristics?

	N [%]	C [%]	m [kg]	MC [%]
Faecal sludge	1.5	15	50,000	50
Market waste	1.5	40	?	65

a) Calculate the needed mass of market waste to obtain a 30:1 ratio.
b) Calculate the operating ratio (actual ratio) between faecal sludge: market waste and compare it with the recommended 1:3.
c) Calculate the moisture content for the mixture and compare to the recommended 40-60 % range.

16. Two drying beds, each with an area of 125 m^2 and a dewatered faecal sludge depth of 15 cm, need to be further treated in a co-compost.
a) How much market waste is needed with an assumed volume ratio required of 1:3 faecal sludge : municipal solid waste?
b) What area for the full treatment process (co-composting and storage) is required if we assume a co-compost cycle of 8 weeks and a drying-bed cycle of 4 weeks?

17. What moisture content and C:N ratio can be expected with the input given in the table below? Evaluate whether the C:N ratio and moisture content are within the ranges of 40-60 % for moisture content and 20-30:1 for the C:N ratio. If not, make a plan of action!

	C [%]	N [%]	Moisture content [weight %]	m [kg]
Faecal sludge	11.4	1.1	42	25
Household waste	30	1.4	50	75

18. You have 300 m^2 on which to build your co-compost facility, next to a prior dewatering unit. In the city there is available market waste to use as co-compost input together with the faecal sludge. How much dewatered faecal sludge can you receive? Assume a 1:3 ratio faecal sludge : market waste.

Chapter 3.6

Co-treatment of faecal sludge with wastewater

Miriam Englund and Linda Strande

Learning objectives

- Understand key considerations and potential impacts of co-treatment in sewer-based wastewater treatment systems
- Explain the importance of influent characteristics on modelling of wastewater treatment plant performance
- Understand why wastewater treatment plants are complex systems with processes that can be disturbed

Textbook

Available at www.sandec.ch/fsm_book

- Strande, L., Ronteltap, M. and Brdjanovic, D. (2014). *Faecal Sludge Management - Systems Approach for Implementation and Operation.*

Free online course (MOOC)

Available at www.eawag.ch/mooc

- *Introduction to Faecal Sludge Management.* MOOC series by Eawag and EPFL. Module ´Co-treatment with Wastewater´.

Further Eawag-Sandec publications

Available at www.sandec.ch/fsm_tools

- Englund, M., Carbajal, J.P. and Strande, L. (2018). *Method to Estimate Quantities and Qualities of Faecal Sludge.* Sandec News 2018.

Additional resources

- Metcalf & Eddy (2014). *Wastewater Engineering: Treatment and Resource Recovery.* 5th Edition. McGraw-Hill, New York.
- Tayler, K. (2018). *Faecal sludge and septage treatment – a guide for low and middle income countries.* Rugby, UK, Practical Action Publishing.
- USEPA (1984). *Handbook: Septage treatment and disposal*, EPA/625/6-84/009. United States Environmental Protection Agency, United States.
- Von Sperling, M. and De Lemos Chernicharo Augustos, C. (2005). *Biological Wastewater Treatment in Warm Climate Regions.*

Introduction

If an area is served by both centralized, sewer-based sanitation and on-site sanitation technologies, it can be efficient to manage and treat them together. However, the risk of failure is high, and the consequences of failure are significant, so the options must be carefully considered and managed. Faecal sludge can have higher concentrations of TS, organic matter and nutrients than wastewater, is more variable (by 1-2 orders of magnitude), and has varying levels of stabilization. Hence, faecal sludge cannot necessarily be treated in the same ways as domestic centralized wastewater. The focus of this chapter is how to modify existing centralized wastewater treatment plants for co-treatment with faecal sludge; note also, that the same considerations are relevant for designs of new co-treatment plants.

Discharging faecal sludge into sewers is not recommended, although treating with a supernatant stream following dewatering can be a possibility. Sewers are designed for the gravity flow of wastewater, and thicker faecal sludge does not have the same flow properties. The thicker faecal sludge can result in blockages, preventing wastewater flows and causing overflows (e.g. through manholes and pumping stations). Loadings at the subsequent treatment plant must also be considered. To avoid shock loadings, the preferred method for co-treatment of faecal sludge would be a continuous flow at a rate that is proportional to the wastewater influent, not only volumetrically, but also considering its characteristics. If there is adequate space, influent variability could be reduced with homogenization tanks.

It is also **NOT** recommended to directly discharge faecal sludge into the headworks of a wastewater treatment plant. This can cause aeration technologies to become over-stressed, resulting in aerobic processes to turn anaerobic, incomplete oxidation, filamentous bacteria, and overloading of settling tanks and clarifiers. For more information, refer to chapter 9 in Faecal Sludge Management - Systems Approach for Implementation and Operation and Module Co-treatment with Wastewater in the *Introduction to Faecal Sludge Management* MOOC.

If an existing wastewater treatment plant is currently under capacity, there are two ways that co-treatment with faecal sludge can be considered, see Table 3.6.1.

Table 3.6.1 Two options for process flow integration.

Option 1.	Option 2.
Dewater the faecal sludge and treat the supernatant with liquid wastewater streams, and the solids with wastewater solids (biosolids). Examples of dewatering include settling-thickening tanks, geo-textile bags, drying beds, and mechanical dewatering.	Treat the faecal sludge together with the wastewater solids stream (biosolids). Examples include co-treatment on drying beds, pelletizing, co-composting, and co-digestion in an anaerobic digester.

Evaluate co-treatment with existing treatment plants

The approach taken here is summarized in Table 3.6.2. This is a simplified outline for planning purposes only; in-depth calculations of acceptable loadings and technical adaptions will be required by qualified professionals.

Table 3.6.2 Step-by-step approach for evaluation of co-treatment with existing treatment plants.

Step 1	Form a competent team
Step 2	Assess quantities and qualities of faecal sludge
Step 3	Characterize existing wastewater treatment chain
Step 4	Integrate process flow
Step 5	Model and verify
Step 6	Monitoring and operation

Step 1: Form a competent team

Identify and contract a competent engineering team, with sanitary engineers that have expertise in both faecal sludge and wastewater treatment to understand the complexities of co-treatment. Engineers should be qualified to design and model the proposed modifications, and oversee in-field testing for verification. There should also be adequate expertise at the treatment plant for implementation and operation.

Step 2: Assess quantities and qualities of faecal sludge

Conduct an evaluation of faecal sludge quantities and qualities to determine potential treatment plant loadings (refer to the Sandec news article *Method to Estimate Quantities and Qualities of Faecal Sludge*), including estimating the total future demand.

Step 3: Characterize existing wastewater treatment chain

Evaluate the existing process flow, treatment performance, and treatment capacity for each step in the treatment chain. If the plant is at capacity, not operating as designed or not meeting effluent guidelines, then co-treatment should **not** be considered.

Step 4: Integrate process flow

Based on the results of steps 2 and 3, possibilities for co-treatment can be evaluated. The two possibilities for co-treatment are summarized in Table 3.6.1. It is of utmost importance to investigate options for pre-treatment of the faecal sludge prior to co-treatment, and the potential to incorporate them into existing and future infrastructure (e.g. a settling-thickening tank). No matter how the faecal sludge is integrated into the process flow, it is important to consider not only the consequences of the increased loadings on all the treatment steps but also the final quality of the treated effluent and solids.

Step 5: Model and verify

Model the effects of additional loadings to the existing wastewater treatment plant based on the monitoring data and quantity and quality results. Conduct any additional laboratory tests necessary for validation of the characteristics. Implement co-treatment with a slow start-up period to verify the accuracy of the assumptions and incorporate any necessary modifications.

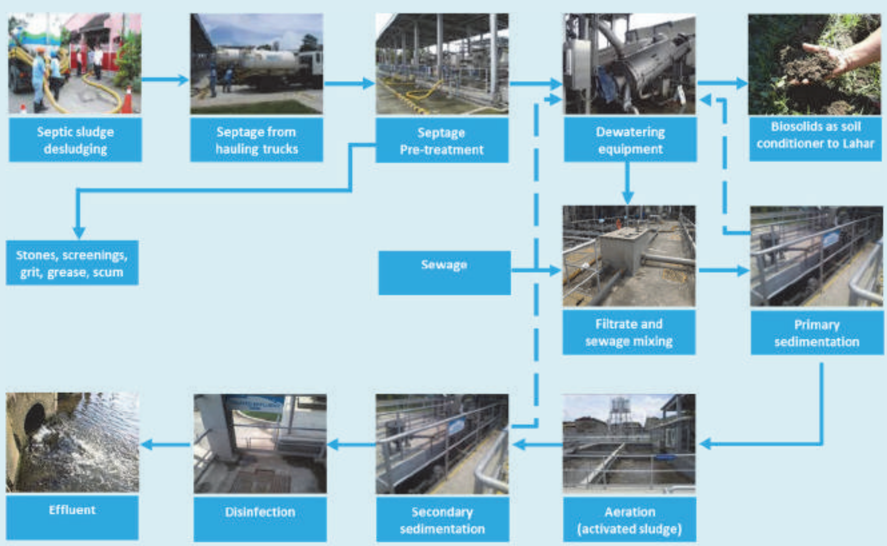
Step 6: Monitoring and operation

Implementation of co-treatment needs to be carefully monitored. Re-evaluate the treatment capacity and performance frequently to monitor for any unforeseen change in influent values. The risk of failure cannot be stressed enough, as co-treatment has been the cause of many treatment plant failures.

Case study 3.6.1 Co-treatment in the Philippines

Information provided from the MOOC series by Eawag and EPFL; Introduction to Faecal Sludge Management.

Manila, the capital of the Philippines, has a successfully operating co-treatment plant. The treatment chain includes faecal sludge dewatering followed by co-treatment of the liquid and solids with the separate solid and liquid streams of the wastewater. The plant treats 2 million litres per day of domestic wastewater and 0.8 million litres per day of faecal sludge (septic tank sludge).



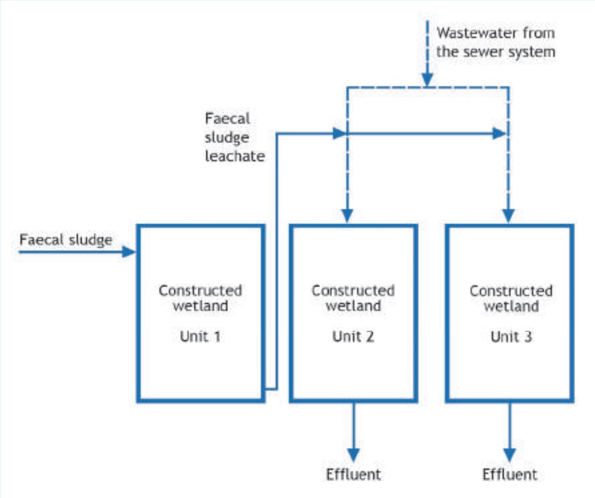
The domestic wastewater treatment chain includes primary sedimentation, activated sludge, clarifiers, and effluent disinfection prior to discharge. The solids are dewatered with the addition of polymers and a screw press, and are then transported off-site by a contractor for further dewatering and drying on drying beds, and then co-composting with rice hulls. The final compost is used as a soil amendment.

The faecal sludge is delivered by vacuum trucks from septic tanks. The faecal sludge treatment starts by screening stones, grits, and sands; oils and scum are removed from the top, and the remaining sludge is dewatered. For dewatering, a polymer is added to flocculate the solids, a screw press is used to separate the solids and liquid, and then the solids are added into the solids processing stream of the wastewater treatment at the screw press stage. The liquid supernatant from the dewatering is added into the headworks of the wastewater treatment plant.

Case study 3.6.2 Co-treatment in Brazil

Information provided from the MOOC series by Eawag and EPFL; Introduction to Faecal Sludge Management.

Belo Horizonte, in the state of Minas Gerais, Brazil, has a well-developed sewer network, together with low-income areas served by septic tanks. Domestic wastewater treatment occurs in three parallel vertical flow constructed wetlands that have been operational since 2009. They operate in a weekly cycle of feeding and resting. Wastewater is directly loaded in batches onto one of the beds following screening and grit removal. A study was carried out to test the feasibility of co-treating the septic tank sludge with the existing wastewater treatment according to option 1, mentioned in Table 3.6.1, in constructed wetlands. Faecal sludge was first treated in Unit 1 and then the leachate was mixed with the incoming wastewater for co-treatment in unit two and unit three. The results showed that the leachate of faecal sludge co-treated on constructed wetlands could be effectively treated.



If co-treatment is planned and adopted adequately, both high and low-cost treatment chains can be successfully utilized for co-treatment.

Exercises

1. What are the reasons why co-treatment of domestic centralized wastewater and faecal sludge fail? Provide an example.
2. Faecal sludge and domestic wastewater can have very different characteristics. Name three characteristics, and how they could impact subsequent treatment steps in a wastewater treatment plant.
3. The risk of failure with co-treatment can be high, resulting in the inadequate treatment of BOTH wastewater and faecal sludge streams. However, there can also be benefits if properly implemented and operated. Name three.
4. Provide an example of how gravity sewer infrastructure can be utilized for transport of faecal sludge to treatment plants, and provide benefits and challenges of this approach.
5. There are two ways of integrating faecal sludge into a wastewater treatment plant if the existing infrastructure has adequate capacity. Describe both of them including drawing a process flow.
6. BOD is a common metric used for influent of wastewater treatment. Explain potential problems with basing co-treatment of faecal sludge on BOD measurements.
7. When designing for co-treatment each treatment unit in the entire treatment chain needs to be carefully evaluated for treatment performance and capacity. List five concerns when designing co-treatment for a conventional activated sludge treatment chain (e.g. primary settling, activated sludge, secondary clarifiers, mechanical dewatering of sludge, and anaerobic digestion).
8. Anaerobic treatment technologies are commonly used in both wastewater and faecal sludge treatment.
   a) List anaerobic wastewater treatment technologies that could be considered for co- treatment of faecal sludge.
   b) List three common parameters that can result in overloading in co-treatment with anaerobic treatment technologies.
9. Provide a brief overview and description of the required steps in a planning process for implementation of co-treatment.
10. Daily loadings of faecal sludge at treatment plants typically have a quite different pattern to domestic wastewater, presenting a challenge for co-treatment. Explain why, and provide management solutions.
11. Faecal sludge is frequently classified as fresh or digested, and as low, medium or high strength. You are operating an anaerobic wastewater treatment plant, and you are asked to start receiving digested, high-strength faecal sludge. What are your concerns?
12. If co-treatment of faecal sludge is attempted at a wastewater treatment plant that is already at full capacity, what are potential outcomes? Provide at least five scenarios with a brief description.
13. You are monitoring the effluent of a conventional activated sludge treatment plant that has started receiving faecal sludge. Effluent COD values are too high. What are the possible explanations?

14. You are working at a treatment plant co-treating faecal sludge and wastewater. The current design is that incoming faecal sludge is treated together with the solids handling of the wastewater (see S4 in Figure 3.6.1). The treatment plant effluent values have increased significantly and you determine based on monitoring that it is due to the incoming faecal sludge. You therefore decide to implement dewatering pre-treatment prior to adding the faecal sludge into the treatment stream.
    a) Provide three examples of faecal sludge pre-treatment options for dewatering.
    b) Write a description of how you would implement the modifications and subsequent monitoring steps.

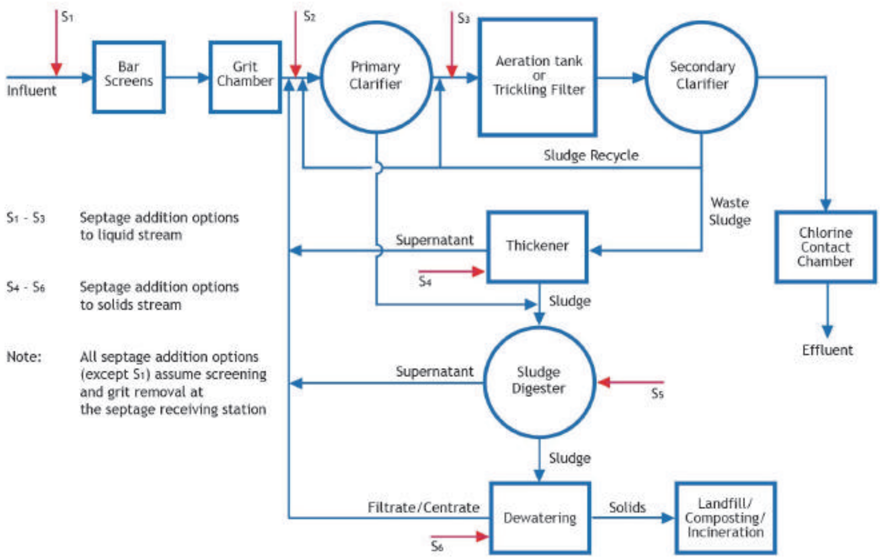


Figure 3.6.1 Points of faecal sludge (septage) addition to a wastewater treatment plant, taken from the EPA Handbook on Septage Treatment and Disposal (USEPA, 1984).

15. You are operating unplanted drying beds with a total surface area of 1,000 m^2. The actual operational solids loading rate is 100 kg TS/m^2.yr, but the design capacity is 250 kg TS/m^2.yr. How much additional faecal sludge per day can the unplanted drying beds receive, if the TS concentration is 12,000 mg/L? Assume the plant is operating 7 days a week, and also has the capacity for the additional leachate treatment.

16. Based on the wastewater treatment chain in Figure 3.6.1, if you are adding dewatered faecal sludge from geo-textiles, where in the treatment chain would you integrate the liquid and solid flows? What information do you need to find out prior to process integration?

17. You are a professional engineer, and are asked to develop an approach to evaluate the possibility of co-treatment for an existing treatment plant. Describe in 200 words the important steps to take, and what needs to be considered.

Chapter 3.7

Effluent treatment technologies

Miriam Englund and Linda Strande

Learning objectives

- Name potential differences between effluents and compare them to wastewater
- Name potential technologies for effluent treatment
- Name potential challenges with effluent treatment

Textbook

Available at www.sandec.ch/fsm_book

- Strande, L., Ronteltap, M. and Brdjanovic, D. (2014). *Faecal Sludge Management - Systems Approach for Implementation and Operation.*

Free online course (MOOC)

Available at www.eawag.ch/mooc

- *Introduction to Faecal Sludge Management.* MOOC series by Eawag and EPFL. Module ´Effluent treatment technologies'.

Further Eawag-Sandec publications

Available at www.sandec.ch/fsm_tools

- Heinss, U., Larmie, S.A. and Strauss, M. (1998). *Solids Separation and Pond Systems for the Treatment of Faecal Sludges in the Tropics. Lessons Learnt and Recommendations for Preliminary Design.* Sandec Report No. 5/98. 2nd edition.
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- Tilley, E., Ulrich, L., Lüthi, C., Reymond, P. and Zurbrügg, C. (2014). *Compendium of Sanitation Systems and Technologies. 2nd edition.* Dübendorf, Switzerland, Eawag - Swiss Federal Institute of Aquatic Science and Technology. www.sandec.ch/compendium

Additional resources

- Cofie, O.O., Agbottah, S., Strauss, M., Esseku, H., Montangero, A., Awuah, E. and Koné, D. (2006). *Solid-liquid separation of faecal sludge using drying beds in Ghana: Implications for nutrient recycling in urban agriculture.* Water Research, 40(1), 75-82.
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- Koottatep, T., Surinkul, N., Polprasert, C., Kamal, A.S.M., Koné, D., Montangero, A. and Strauss, M. (2004). *Treatment of septage in constructed wetlands in tropical climate – Lessons learnt after seven years of operation.* Water Science and Technology, 51(9), 119-126.
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- Metcalf & Eddy (2014). *Wastewater Engineering: Treatment and Resource Recovery.* 5th Edition, McGraw-Hill, New York.
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- Von Sperling, M. and De Lemos Chernicharo Augustos, C. (2005). *Biological Wastewater Treatment in Warm Climate Regions.* IWA publishing.
- World Health Organization (WHO) (2015). *Wastewater Use in Agriculture. Guidelines for the Safe Use of Wastewater, Excreta and Greywater.*
- World Health Organization (WHO) (2018). *Guidelines on Sanitation and Health.*

Introduction

In general, liquid streams that come from faecal sludge treatment technologies, and are discharged to the environment, are referred to as effluent. Leachate refers specifically to liquid that is drained (or percolates, or is leached) from drying beds, which still requires further treatment prior to discharge. Concentrations of constituents in the effluent are dependent on factors such as the influent characteristics, the treatment technology chain, and treatment performance. Compared to conventional domestic wastewater influent, the liquid stream from faecal sludge treatment technologies such as drying beds, typically has higher concentrations of organics, nutrients and salts, as shown in the example in Table 3.7.1.

Table 3.7.1 Leachate characteristics following drying beds, compared to domestic wastewater influent, and discharge standards. References: Koottatep *et al.* (2004); Heinss *et al.* (1998); Von Sperling *et al.* (2005); Sonko *et al.* (2014); Manga *et al.* (2016); NEMA (1999); Kone *et al.* (2007); Cofie *et al.* (2006); Strande *et al.* (2014).

Parameter	Unit	Leachate unplanted drying beds	Leachate planted drying beds	Influent domestic wastewater	Effluent discharge standards
TSS	mg/L	290-720	49-730	200-450	10-100
COD	mg O_2/L	3,600-6,500	92-2,200	450-800	50-200
Ammonium nitrogen	mg/L	150-520	5-200	20-35	5-30

The engineering design approach sets treatment objectives based on local effluent discharge standards or on the desired enduse. Effluents can have salt concentrations that are too high for irrigation, ammonia concentrations that can be harmful to plants, ammonia and organic concentrations that have negative impacts on aquatic environments, and high levels of pathogens. Therefore, it is important to consider the appropriate levels of treatment for the enduse.

There are important differences between effluent from faecal sludge treatment compared to influent domestic wastewater to consider when designing treatment solutions. Effluent from faecal sludge treatment tends to have:

- Higher concentrations of total organic matter (as COD), however, the biodegradable COD fraction can be lower due to the longer onsite retention time. This is important to consider in biological processes for the stabilization of organic matter.
- Higher ammonia concentrations. This is important to consider, as it can inhibit biological processes.
- More variability in the quantities and qualities arriving at the treatment plant. As a result, it is important to consider actual concentrations, rather than using percent removals, as well as minimums and maximums, rather than averages. Equalization tanks are one example of potential measures that can be put in place to buffer quantities and qualities.

Examples of treatment technologies and their treatment objectives

There are several established treatment technologies that work well for effluent depending on the available space. For example, infiltration beds, planted drying beds, constructed wetlands, anaerobic baffled reactors (ABR), waste stabilization ponds and anaerobic filters. These technologies have proved their reliability and capacity to treat high organic loading from faecal sludge effluent. They do not require a constant energy supply and only need light operation and maintenance. Other technologies that could potentially be transferred from wastewater treatment include activated sludge processes, moving bed bioreactors, trickling filters or sequence batch reactors. These might reach better effluent standards and require less land. However, they need a constant energy supply, are more expensive, require skilled operators and their ability to handle hydraulic and organic shock loads inherent to faecal sludge effluent has not been confirmed. While designing the effluent treatment system, all these parameters have to be carefully evaluated in regards to the local context. For more information on designing technologies, please refer to *Domestic wastewater treatment in developing countries,* Mara (2013).

Step-by-step approach for selection of effluent treatment

The approach taken here to determine the appropriate effluent treatment technology is summarized in Table 3.7.2. This is a simplified outline for **planning** purposes. In-depth calculations of acceptable loadings and technical adaptions made by qualified professionals are also required.

Table 3.7.2 Step-by-step approach for selection of effluent treatment.

Step 1	Define treatment objectives
Step 2	Assess faecal sludge pre-treatment
Step 3	Assess faecal sludge effluent quantity and quality
Step 4	Select appropriate effluent treatment technology
Step 5	Monitor and operate

Step 1: Define treatment objectives

Identify what the treatment needs to achieve. This includes defining the enduse/disposal of the treated effluent and the corresponding local effluent application/discharge standards that have to be reached. If local standards are not available, use international guidelines and a risk-based approach depending on the intended enduse or disposal (e.g. *Guidelines for the Safe Use of Wastewater, Excreta and Greywater,* WHO, 2015; *Guidelines on Sanitation and Health,* WHO, 2018).

Step 2: Assess faecal sludge pre-treatment

The faecal sludge treatment chain will influence the quantity and quality of the effluent and whether it needs further treatment prior to discharge. For example, settling-thickening tanks, unplanted or planted drying beds will result in different hydraulic loads and nutrient levels in the effluent. Therefore, it is important to understand which treatment steps the faecal sludge is undergoing to be able to evaluate the quantities and qualities that will be handled.

Step 3: Assess faecal sludge effluent quantity and quality

Based on the treatment chain identified in step 2, calculate the quantity (e.g. hydraulic load) and quality (e.g. COD, nutrient and pathogen concentration) of the faecal sludge effluent that needs to be treated prior to discharge. It is crucial to understand not only the dynamic of the quantities and qualities from the respective treatment technology, but also the full chain in order to choose and properly dimension the treatment technologies.

Step 4: Select appropriate effluent treatment technology

Knowing the quantity and quality of faecal sludge effluent as well as the effluent standards for the enduse will define the amount of pollutant that has to be removed from the effluent. With this required level of treatment in mind together with other local specific parameters (e.g. availability of land, electricity, operation and maintenance capacity and financial resources), select the most appropriate treatment technology. The treatment design also needs to take the variability of the quantities and qualities of faecal sludge into account.

Step 5: Monitor and operate

The operation and maintenance of the effluent treatment has to be carried out by qualified staff according to the selected treatment options, for example, if the biological nature of the treatment is complex and sensitive to inflow fluctuation. If transferring or innovative technologies are selected, they need to be closely monitored so the operation can be adapted as needed. Refer to chapter 3.1 Overview of treatment technologies for more information.

Example 3.7.1 Effluent treatment in practice

Example provided by Fichtner Consulting Engineers Ltd

Based on their experience with design and operation of effluent treatment for faecal sludge, Fichtner has identified key considerations that should be taken into account when designing effluent treatment. It is also important to keep in mind that due to the high volumes, to achieve adequate treatment of effluent for discharge into the environment can be challenging.

Established treatment technologies for effluent treatment include waste stabilization ponds (anaerobic, facultative and aerobic maturation) and constructed wetlands. However, the high concentrations of BOD, COD, TSS and nutrients in the effluent of faecal sludge treatment complicates the treatment process in comparison to wastewater treatment. For example, faecal sludge has high COD/BOD ratios, Fichtner has seen up to 10 in comparison to 2 for conventional wastewater. With high influent concentrations, it is important to keep in mind, that even if a treatment process has a 97.1% removal efficiency, with an influent COD of 8,400 mg/L, the effluent will only be reduced to 240 mg/L, which would still not reach an effluent standard of 100 mg/L.

To illustrate the importance of this with theoretical calculations, the required treatment footprint for waste stabilization ponds treating drying bed leachate prior to effluent discharge, would be the same for a plant with 400 m^3 faecal sludge treatment capacity, with or without co-treatment of 6,000 m^3 per day wastewater. This is because the leachate stream is so much more concentrated than conventional wastewater. For this reason and the impact of required treatment space, if possible, it is best to locate faecal sludge and wastewater treatment plants together for co-treatment of effluent.

Another possibility is to introduce a flocculation unit prior to co-treatment to reduce the organic loading to the co-treatment. Alum sulphate has been used for this purpose in Dakar, Senegal, see Figure 3.7.1. For more information on conditioners, refer to chapter 5.2.

Figure 3.7.1 The flocculation unit at a faecal sludge treatment plant in Dakar, Senegal. Operated by DELVIC Sanitation Initiatives.

For smaller scale treatment facilities where there are no neighbouring wastewater treatment plants, and adequate land availability, constructed wetlands are a good option for effluent treatment. In this case, the effluent treatment can be combined with irrigation or infiltration. Rainy seasons and ground water levels need to be taken into account.

Case study 3.7.1 Irrigation as effluent treatment

Case study provided by BORDA.

In Dar es Salaam, Tanzania, BORDA operates three faecal sludge treatment plants where the treated effluent is used for irrigation in banana tree plantations.

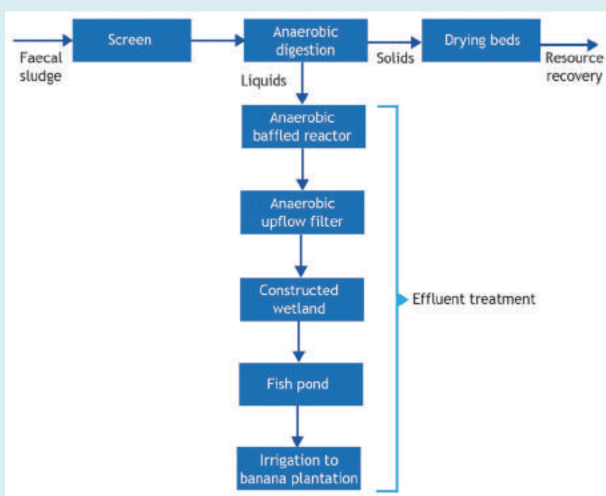


Figure 3.7.2. Process flow of the faecal sludge treatment plant in Kigamboni, Dar Es Salaam.

Case Study 3.7.2 Series of planted drying beds as effluent treatment

Case study based on Kengne et al. (2014).

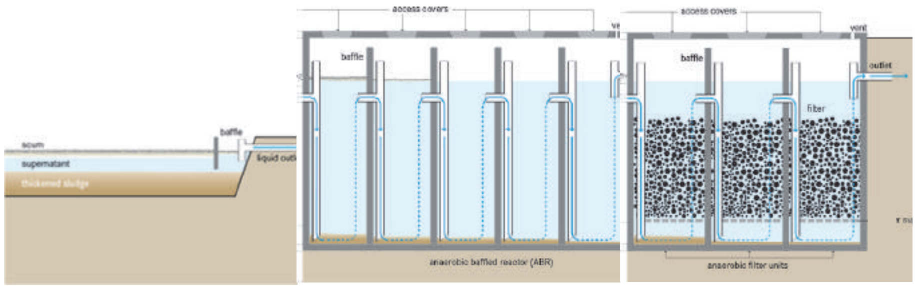
At the University of Yaounde I in Cameroon, a pilot-scale faecal sludge treatment plant consisted of a planted drying bed for dewatering followed by another series of planted drying beds (or 'vertical flow constructed wetlands') for effluent treatment, see Figure 3.7.3. This treatment chain also generated plants that could be used as animal fodder, and solids for use as a soil conditioner. During the pilot-scale study, hydraulic loading rates of 50, 100 and 150 mm of faecal sludge/day were all showed to be sufficient to meet the WHO and national guideline thresholds for discharge or reuse in non-restricted agriculture for all the monitored parameters except nitrogen and faecal bioindicators. Total Kjeldahl Nitrogen (TKN) and faecal coliforms had a mean value and standard deviation of 105.39±31.17 mg/L and 5.26±5.40 log CFU/100 mL compared to the discharge standards of <30 mg/L and <3.30 log CFU/100 mL. This could potentially be managed by adding a second series of planted drying beds for effluent polishing, or by periodically flooding the beds to achieve denitrification. The study demonstrates that planted drying beds can be operated effectively at any of these loading rates, are adaptable to different size treatment schemes, and are resistant to changes in loading rates (Kengne *et al.,* 2008).

Figure 3.7.3 Process flow for the pilot-scale faecal sludge and effluent treatment conducted by the University of Yaounde I.

Exercises

1. Give three potential effluent treatment technologies and describe the respective process for each of the technologies in two sentences.
2. Name four concerns when treating faecal sludge liquid effluents.
3. Why and how are faecal sludge effluent characteristics different from wastewater effluent? Give three key considerations and why they matter.
4. Waste stabilization ponds are common effluent treatment technologies.
   a) Name the types of waste stabilization ponds that are normally designed in series and their treatment objectives.
   b) What is the benefit of working with ponds in series?
5. How do the high ammonia concentrations in faecal sludge affect waste stabilization ponds?
6. What is the primary purpose of an anaerobic baffled reactor?
7. Horizontal flow constructed wetlands and planted drying beds (or vertical flow constructed wetlands) can both be used for the biological treatment of effluent from faecal sludge treatment plants. Explain the two different treatment technologies, how they can be designed and operated, and their treatment mechanisms.
8. Especially in water-scarce regions, water reclamation of the effluent is beneficial, for example in irrigation or fish cultivation. Name three water quality parameters that are important to monitor for these purposes, and what risks their monitoring is managing.
9. An aerobic maturation pond is a common effluent treatment technology in combination with anaerobic and facultative ponds. What treatment objective is the aerobic maturation pond possibly designed for? Explain the process in brief.
   a) Stabilization
   b) Pathogen inactivation
   c) Nutrient management
10. The variability of TSS and TS of faecal sludge treatment plants effluent is important. What would be the impact of an increase in their concentration on the operation and maintenance of liquid effluent treatment technologies such as anaerobic filters or ABRs?
11. Explain the function **and** treatment mechanisms of an anaerobic filter.
12. Effluent from faecal sludge treatment technologies can have high ammonium concentrations that complicate biological treatment processes, which is challenging in facultative ponds. How does the high ammonia concentration decrease treatment performance on facultative ponds?
13. You are a fish farmer operating a faecal sludge treatment plant in Honduras. You have noticed that the organic matter in the effluent is far too high, resulting in anaerobic conditions (depleted oxygen) in the fish ponds. The current system consists of an anaerobic digester, followed by a planted drying bed for treatment of the digestate, and the effluent is discharged into the fish ponds. Give a treatment technology **and** where you would place it that will help you to reduce the organic matter.

14. At a faecal sludge treatment plant, a series of anaerobic baffled reactors and anaerobic filters are connected as effluent treatment following a settling-thickening tank. Effluent with increased TSS is coming out from the settling-thickening tank, and as a consequence, the anaerobic filter has started to clog. Give two possible measures to handle the situation.



Settling-thickening tank (Images: Tilley *et al.*, 2014). Anaerobic baffled reactor Anaerobic filter

15. Treated liquid effluent can typically be used for irrigation purposes. Name and describe two treatment technologies that can be used for managing nutrient levels in liquid effluent for irrigation purposes.

16. Faecal sludge that is discharged at treatment plants can have highly variable characteristics. One influencing parameter can be the storage time. How can faecal sludge characteristics with short-term (days) or long-term (years) storage in onsite containment differ, and what are some possible implications for the treatment technologies?

Chapter 4.1

Integrated planning approach

Christoph Lüthi

Learning objectives

- Understand the importance of an integrated approach for faecal sludge management
- Understand the importance of participation
- Learn how to plan a faecal sludge management project on a city level and include all necessary steps and activities

Textbook

Available at www.sandec.ch/fsm_book

- Strande, L., Ronteltap, M. and Brdjanovic, D. (2014). *Faecal Sludge Management - Systems Approach for Implementation and Operation.*

Free online courses (MOOCs)

Available at www.eawag.ch/mooc

- *Introduction to Faecal Sludge Management*. MOOC series by Eawag and EPFL. Module 'Integrated planning approach'.
- *Planning & Design of Sanitation Systems and Technologies*. MOOC series by Eawag and EPFL.

Further Eawag-Sandec publications

Available at www.sandec.ch/fsm_tools

- Tilley, E., Ulrich, L., Lüthi, C., Reymond, P. and Zurbrügg, C. (2014). *Compendium of Sanitation Systems and Technologies (2nd edition).* Dübendorf, Switzerland, Swiss Federal Institute of Aquatic Science and Technology (Eawag). www.sandec.ch/compendium
- Parkinson, J., Lüthi, C. and Walther, D. (2014). *Sanitation 21 – a planning framework for improving city-wide sanitation services.* IWAP, London, UK www.susana.org/en/knowledge-hub/resources-and-publications/library/details/2712
- Lüthi, C., Morel, A., Tilley, E. and Ulrich, L. (2011) *Community-Led Urban Environmental Sanitation (CLUES).* Dübendorf, Switzerland, Swiss Federal Institute of Aquatic Science and Technology (Eawag). www.sandec.ch/clues

> **Additional resources**
> - Blackett, I. and Hawkins, P. (2017). *FSM Innovation Case Studies - Case Studies on the Business, Policy and Technology of Faecal Sludge Management (2nd edition).* Bill & Melinda Gates Foundation, Seattle, USA, ISBN 978-1-5136-2513-3.
> - Tayler, K. (2018). *Faecal sludge and septage treatment – a guide for low and middle income countries.* Rugby, UK, Practical Action Publishing.

Introduction

Citywide sanitation is cross-sectoral in nature and involves various stakeholders. An integrated systems-level approach that incorporates technology, management and planning is necessary for a well-functioning faecal sludge management service chain. It is important to realise that faecal sludge management is just one of several system options (i.e. sewers, decentralized sewers, onsite sanitation) in cities in low and middle-income countries. Figure 4.1.1 shows blended sanitation systems in a typical urban setting (blue: sewered; green: small-scale sewered systems; brown: onsite sanitation served by faecal sludge management).

Virtually all low-income settlements and a good proportion of high-income housing depend on onsite systems, typically pit latrines in the poor areas and septic tanks in the rich areas. More recent middle-class residential estates or commercial and institutional developments may have decentralised sewerage systems, often privately operated.

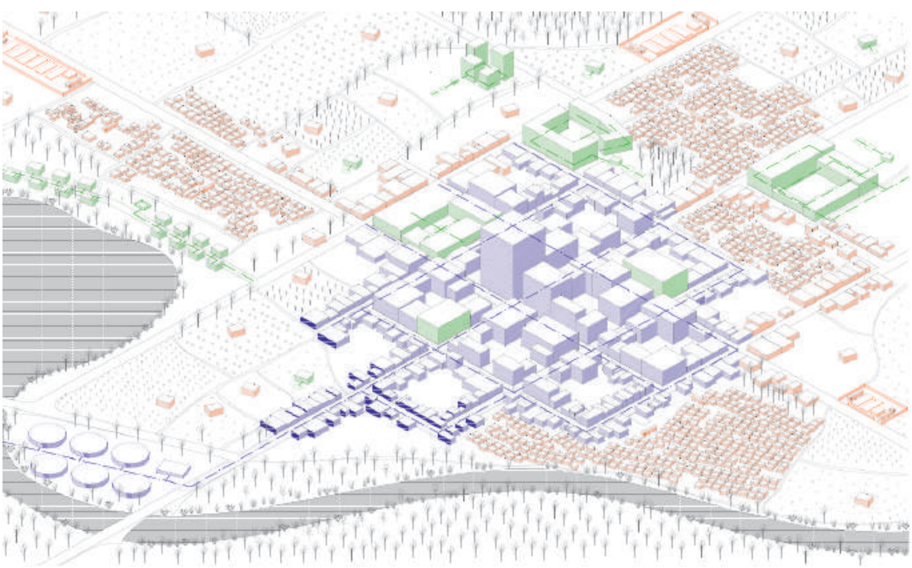


Figure 4.1.1 Blended sanitation systems (Image: Fernandez Cortes, M., Eawag-Sandec).

An integrated planning approach must incorporate the entire sanitation service chain from toilet (user interface) to resource recovery or safe disposal of the faecal sludge. The faecal sludge management planning framework is shown in Figure 4.1.2 'FSM planning from A to Z' which outlines the 26 sub-steps in greater detail. Refer to chapter 17 *Planning integrated faecal sludge systems* by Reymond, P. in the book *Faecal Sludge Management - Systems Approach for Implementation and Operation* (Strande *et al.*, 2014).

Exercises

1. The integrated approach suggests conducting exploratory studies (first step). Why is the exploratory study so important before moving on to detailed pre-feasibility studies?
2. The faecal sludge management framework includes preliminary studies. Why is stakeholder interaction and an initial launching workshop involving all the primary partners considered essential?
3. During the feasibility study, activities (amongst others) such as faecal sludge quantity and quality, site pre-selection and cost parameters are established.
   a) Who is best placed to conduct such a holistic feasibility study in a given context?
   b) What are important factors for the site selection of a future faecal sludge treatment plant?
4. During the detailed project development an action plan is prepared.
   a) Define three areas of a badly developed action plan that can lead to problems later on.
   b) Who could be responsible for implementing the action plan?
5. How can we guarantee a high quality and transparent bidding process during the tendering process?
6. The final step of the integrated planning process is project implementation, and the monitoring and evaluation of it. A crucial step, as several aspects can lead to mistakes and undesirable outcomes. How can we ensure high quality construction of the final hardware?
7. Which is the more important cost factor for the long-term operation of a faecal sludge treatment plant?
   a) Capital expenditure/implementation costs, or
   b) Operational expenditure?

FSM planning from A to Z

eawag aquatic research

Standard project phases		Activities	Outcomes	Chapters	Participatory stages: CLUES	Participatory stages: SAN21
Exploratory study	A	Preliminary assessment of the initial situation and first inventory of stakeholders	Overview of the situation; facilitators are identified	14 15	Process ignition	Establish a city sanitation task force
			Inception report			
Preliminary (pre-feasibility) studies	B	Identification and preliminary characterisation of the stakeholders and their relationships	All stakeholders are identified and characterized	15	Launch of the planning process	Understand the existing context
	C	Initial launching workshop, including field visit with all the stakeholders	Stakeholders are sensitized to sanitation reality and aware about the project's objectives	16.5		
	D	Assessment of: - Sanitation practice and needs, reuse interests - Institutional setup, government support - Legal and regulatory framework - Existing organisational modes - City structure and heterogeneity of sanitation practices - Existing financial flows - Climate	Sanitation practices are identified, as well as urban heterogeneity; Strengths, weaknesses, opportunities and threats are identified (SWOT analysis); The enabling environment is described	14	Detailed assessment of the current situation	
	E	Selection of potential organisational modes	Orientation of the process towards realistic options	12		
	F	Identification of sites for treatment	Stakeholders have indicated existing and potential sites	14.4		
	G	Characterisation and selection of key stakeholders	Stakeholder who have interest in and/or influence on the process are identified	15.4 to 15.5		
			Preliminary studies report			
Feasibility study	H	Quantification and characterisation of sludge	Process leaders know what has to be treated	2	Identification of service options	Identify viable solutions
	I	Characterisation and selection of sites	Appropriate sites are selected	14.4		
	J	Preselection of combinations of technologies, organisational modes and financial mechanisms	Scenarios are elaborated	5,11,12, 13,15,17		
	K	Detailed evaluation of selected options, including: - Requirements of technology combinations, pros and cons, O&M - Organisational mode and institutional setup; roles & responsibilities; contractual arrangements - Capital and operation costs, financial mechanisms, estimated budget - Skills required to run each system - Environmental impact assessment	System scenarios are evaluated and optimised	4-17		
	L	Preliminary presentation of the results to the key stakeholders	Stakeholders are consulted and agreement is secured	16		
	M	Final selection of system options		17		
	N	Workshop : Validation of chosen options by all the stakeholders	Proposals are validated by all stakeholders	16.5		
	O	Reassessment of key stakeholders according to the validated options	Influence and interest of stakeholders are reassessed according to the previous decisions	15.5		
			Feasibility study report			
Detailed project development	P	Detailed project development (Action Plan): - Detailed design of the treatment plant - Detailed definition of roles & responsibilities - O&M management plan with clear allocation of costs, responsibilities and training needs - Conventions between stakeholders, securing financial and institutional mechanisms - Strategy for control and enforcement - Definition of needs for capacity building and job creation - Definition of contracts and bidding processes - M&E strategy for the implementation phase - Timeline for implementation with distinct phases and an itemised implementation budget	The Action Plan is written; The whole system is described in detail	11 12 13 16 17	Development of an Action Plan	Elaborate Strategic Plan
	Q	Workshop : Presentation of the Action Plan	The Action Plan is validated by all stakeholders	16.5		
	R	Reassessment of key stakeholders according to Action Plan	Roles and responsibilities of stakeholders are redefined according to the Action Plan	15.5	Implementation of the Action Plan	Prepare for implementation
			Detailed Project Document			
Implementation	S	Recruitment of contractors for building and O&M		11		
	T	Organisation of the sector, transfer of roles & responsibilities	FS management is transferred to the corresponding stakeholders	11,12,13,16		
	U	Capacity building / information campaigns	Awareness is raised among users; Capacity is built where needed	16		
	V	Monitoring of construction	Building according to state-of-the-art is ensured	11		
	W	Reassessment of key stakeholders before inauguration of the FSTP	Capacity of stakeholders to deal with their new roles and responsibilities is assessed	15.5		
	X	Start-up of the system	The FSTP is brought to its state of equilibrium; stakeholders have acquired the necessary skills	11		
	Y	Official inauguration ceremony	The FSTP is officially transferred to the city authorities / private entrepreneurs			
M&E	Z	Monitoring of the running system (technical stability, satisfaction of stakeholders, cost recovery)	The system is monitored to ensure its sustainability	11		

Figure 4.1.2 The faecal sludge management planning framework. (Image: Reymond, P., Eawag-Sandec).

Reference: Reymond P. (2014). *Planning integrated faecal sludge management systems*. In: Strande, L., Ronteltap, M., Brdjanovic, D. (editors). Faecal Sludge Management: Systems Approach for Implementation and Operation. 432 pg. ISBN: 9781780404721 (Hardback) 9781780404738 (eBook), IWA Publishing, London. 2014. p. 363–387.

Chapter 4.2

Assessment of the initial situation

Samuel Renggli

Learning objectives

- Understand what information is needed at the beginning of the faecal sludge management planning process
- Understand how to assess the initial situation
- Understand the importance of the enabling environment

Textbook

Available at www.sandec.ch/fsm_book

- Strande, L., Ronteltap, M. and Brdjanovic, D. (2014). *Faecal Sludge Management - Systems Approach for Implementation and Operation.*

Free online courses (MOOCs)

Available at www.eawag.ch/mooc

- *Introduction to Faecal Sludge Management*. MOOC series by Eawag and EPFL. Module 'Assessment of the initial situation'.
- *Planning & Design of Sanitation Systems and Technologies*. MOOC series by Eawag and EPFL.

Further Eawag-Sandec publications

- Lüthi, C., Morel, A., Tilley, E. and Ulrich, L. (2011). Community-Led Urban Environmental Sanitation Planning (CLUES). Dübendorf, Switzerland, Swiss Federal Institute of Aquatic Science and Technology (Eawag). Available at www.sandec.ch/clues
- Englund, M., Carbajal, J.P. and Strande, L. (2018). *Method to Estimate Quantities and Qualities of Faecal Sludge*. Sandec News 2018. Eawag-Sandec.
- Tilley, E., Ulrich, L., Lüthi, C., Reymond, P. and Zurbrügg, C. (2014). *Compendium of Sanitation Systems and Technologies. 2nd edition.* Dübendorf, Switzerland, Swiss Federal Institute of Aquatic Science and Technology (Eawag). Available at www.sandec.ch/compendium

Additional resources

- SFD Promotion Initiative (2018). SFD Manual Volumes 1 and 2.
- Tayler, K. (2018). *Faecal sludge and septage treatment – a guide for low and middle income countries.* Rugby, UK, Practical Action Publishing.

Introduction

The main goals of the assessment of the initial situation are to set the scene, understand the context, get to know the stakeholders and provide enough information to start elaborating the faecal sludge management scenarios. This includes, among others, the definition of context-specific design parameters that allows logical plans to be made in order to move forward. This phase of the planning process is therefore characterized by data collection via different means such as maps or Google Earth. The idea is to get a holistic snapshot of the situation. By looking at secondary data, different situations and contexts can be identified such as existing infrastructure services, sewer networks, type of toilets, service providers and how they are organized, and whether the sludge is safely or unsafely managed. This process should include a Q&Q (quantity and quality) study as explained in Englund *et al.* (2018) and an SFD (Shit Flow Diagram) (SFD Promotion Initiative, 2018).

It is extremely important to carry out a stakeholder analysis and also to establish the profile and practices of the manual and mechanical service providers. Furthermore, it is central to understand practices from the household level to the enduser, and the potential market for a treatment product by following an MDA (Market-Driven Approach). To fully understand the stakeholders, the financial transfers between them should be known; for example, how much do households currently pay for collection and transport services? The enabling conditions, see Figure 4.2.1, are critical for successful sanitation investment; however, identifying the gaps enables a plan of action.

Figure 4.2.1 The enabling environment for faecal sludge management in a city (taken from Lüthi *et al.*, 2011) .

Data collected will help to estimate faecal sludge quantities and qualities (Q&Q) and context-specific design parameters for future faecal sludge treatment plants. It is important to identify potential land for a treatment site at the earliest opportunity as very frequently there is no available land. Land is expensive and/or people are not willing to have a treatment plant in their neighbourhood.

In large urban areas it is recommended to have several treatment plants at different locations. When deciding the level of decentralization, the mechanical service providers should be at the core of the decision. The service providers have the necessary information on the current disposal sites and are aware of the constraints of their business (problems with traffic, the average distance and duration of the trips, and the revenue). Larger treatment plants require on average longer haulage distances from the pits, implying higher costs for the collection and transport companies. Companies then have two choices: either increase the tariff for the households, which may threaten the affordability of the service, or use closer illegal disposal sites. There are examples of faecal sludge treatment plants which have never been used because they were too far away or not accessible. For more information about collection and transport of faecal sludge see chapter 2.5.

The best way to acquire accurate information is to collect it from different sources and then validate the data. Data can be gathered, amongst other, through a literature review, semi-structured interviews, household surveys, and qualitative field observation. It is important to communicate the results from the data analysis in a form that is understandable and can be utilized by the different stakeholders.

A SWOT analysis is one way of displaying the data. The SWOT analysis systematically evaluates the strengths, weaknesses, opportunities and threats for the implementation of a proper faecal sludge management scheme in a city. This assessment can be conducted more systematically by considering each of the enabling environment components. The SFD is also an effective way to represent in one figure the main results of the initial assessment of the situation and it provides a good advocacy tool to use with the authorities.

The quality of the initial assessment of the situation and the way it is communicated is important for the success of the future faecal sludge management activity. Note also the importance of trust building during the assessment study. Trust is the most efficient way of securing a successful project, accessing information and getting stakeholders on board.

How to assess the initial situation

Table 4.2.1 summarizes the steps to assess the initial situation when planning for faecal sludge management services. For more information about the initial assessment (including the five steps) refer to chapter 14 - Assessment of the initial situation, in Faecal Sludge Management - Systems Approach for Implementation and Operation (Strande *et al.,* 2014).

Table 4.2.1 Steps for the assessment of the initial faecal sludge management situation.

Step 1	Collect secondary data
Step 2	Analyse the stakeholders and the enabling environment
Step 3	Collect primary data
Step 4	Analyse the data
Step 5	Display and communicate the data

Step 1: Collect secondary data

Some of the questions that can be asked in this first step are listed below (this list is by no means complete). Ideally all the existing secondary data is collected through government documents, old project reports and existing maps.

- What are the existing infrastructure services?
- Are there sewer networks?
- Which types of toilets exist?
- Who are the service providers and how are they organized?
- What are the demographics?
- How is WASH managed?
- What are the climatic conditions?

Step 2: Analyse the stakeholders and the enabling environment

The enabling environment consists of six categories, see Figure 4.2.1, and should be evaluated by asking the questions listed below, for example, through the use of the SWOT methodology.

- What is the government support?
- What is the legal and regulatory framework?
- What are the rules but also where are the gaps?
- Which are the relevant institutions and how are they organized? What are the skills and capacities, especially in terms of human resources and management?
- What are the financial arrangements?
- What is the socio-cultural acceptance of the different options?

Step 3: Collect primary data

After gaining an overview, primary data should be collected. The data collection should focus on collecting spatial data on the demographics, environment and technical information and establish faecal sludge quantities and qualities (Q&Q); for more information refer to the Q&Q method in Englund *et al.* (2018). Different data collection methods can be used:

- A sampling campaign
- A household survey
- Semi-structured interviews with stakeholders
- Focus group discussions
- Mapping

Step 4: Analyse the data

Depending on the form of data collection and on the reader, it can be analysed in different formats. It is important that this data analysis is comprehensible for different kinds of stakeholders ranging from informal collection and transport services to the mayor of a city.

Step 5: Display and communicate the data

The data is then displayed and communicated in a meaningful way appropriate to the target audience. Potential tools are:

- A Shit Flow Diagram (SFD)
- SWOT analysis
- Workshops

Exercises

Case study: Faekonia, Faraway

You are hired by the Government of Faraway to analyse the faecal sludge management (FSM) situation in the city of Faekonia, as they plan to improve FSM in various Farawayan cities with governmental funding. The first step is to gain an overview through secondary data. This has been done through consulting existing reports and documents and a first transect walk through the area, and this initial overview is described below. Please read carefully and then answer the questions that follow in the end. The information in this case study is based on actual conditions in an existing city; however, some information has been modified.

City profile

Faekonia became the capital city of the central Farawayan state Chhattisgarh, which was founded in 2000. Being the only major agricultural, commercial, industrial and educational centre in the region, Faekonia has since attracted large numbers of immigrants. Over the last 10 years Faekonia's population has grown by a total of 44% or an average of 3.7% annually. In 2011, according to the census there was a total of 1.01 million inhabitants, of which 124,471 were children between 0 and 6 years. The city population spreads over an area of 226 km^2. The city of Faekonia is politically divided into 71 wards (geographical areas) and the residents of each ward elect a councillor, who represents them in the municipal parliament.
Migrants from rural areas are attracted to the city by employment opportunities. The city is very dynamic with lots of construction of large-scale infrastructure taking place. This, however, has increased the price of the already scarce land for housing and people with a low income are unable to afford housing in the formal land market. Thus they are compelled to live in the city's low-income and underserved informal settlements (slums). Since 2001, the slum population has increased by 264% and it is estimated that 520,000 people are living in the 284 officially recognized slums. Almost 91% of all the slum settlements are located within 5 km of the city centre and together occupy around 5% of the land in the city. Faekonia is located at an altitude of 300 meters above sea level. It features a rather flat terrain with a general slope towards North-East. The area is characterized by a tropical wet and then hot and dry season with highest temperatures from March to June.

Project area

The project area is in Ward number 7, which is north of the centre of Faekonia. Ward 7 comprises three neighbouring slum settlements:

- Satnami Para I (around 200 households)
- Sahu Para (around 700 households)
- Baramdei Para (around 400 households)

The project area is generally flat with a slight slope towards the main street in the East. In Ward 7, most of the land is privately owned. Another part of the land is Abadi land. This is government-owned but residents have been granted 'pattas' by the revenue department of the Faekonia Municipal Corporation. A 'patta' is a legal document that gives a long-term temporary right to use the land (up to a maximum of 30 years). The 'patta' dwellers pay a monthly tax to the government, which proves their residence and in principle gives them the right to obtain access to cooking gas, a private water tap and an electricity connection. There are several schools and a small healthcare facility in the area, as well as a small market along the main road.

Water supply and sanitation

Water connection is quite good in the area, with more than 80% of households having a domestic water connection and paying a monthly fee. About 50% of the households in the project area have toilets within their homes, of which most are squatting pour-flush toilets. Some have connected the pour-flush toilets to single pits and others to septic tanks. The liquid in the pit latrines infiltrates into the soil. As the pits are very deep, the accumulated sludge has not been emptied so far. The septic tank effluent typically flows into ponds or into the environment either directly or indirectly via the open drains. Some of the septic tanks are very old, making it likely that they also discharge solids together with the effluent. There is one designated public toilet in the ward but there is no formalized management. On the other side of the main street, opposite the market just outside of the project area, are some other public toilets built and maintained by Sulabh, a big provider of public toilets in Faraway. The users are charged 5 Rs per adult and 3 Rs per child. Monthly cards are also issued for 50 Rs per person per month. Most of these Sulabh toilets, however, are poorly maintained. Open defecation in designated areas is still quite common and practised by more than half of the slum population. Particularly children defecate in open areas or in open drains, even though many of them live in households with a toilet. Some people use public unimproved latrines; this is usually a curtain made of old fabrics or plastics, built over an open drain or over a pond (hanging toilets). A trunk sewer was built under the main street. This sewer leads to a pump house. However, the pump house has been out of operation for a few years and therefore the sewer has not been functional either. None of the houses in the project area are connected to the sewer, except illegal connections; therefore almost no water is running in the sewer. Connecting the area to the sewer is difficult but not impossible from a technical point of view. However, the willingness of the householders to connect to the sewer is very low given the capital cost to build and install the piping to the sewer.

Stakeholder and enabling environment

Several stakeholders have been identified. The Public Health Engineering Department (PHED) of the city of Faekonia is responsible for provision of water and sanitation services within the city. The institution is willing to learn more about FSM but has low capacity and little experience. The Mayor of the city of Faekonia does not show any interest in FSM. The Ward Councillor of Ward 7 is from an opposing party to the Mayor and is mainly concerned about re-election but knows the area and the people very well. There are several informal septic tank and pit latrine emptiers. The PHED also has a big vacuum truck, but it can only access the main roads and emptying fees are twice as high as for the informal emptiers. They empty into a designated wetland outside the city. The informal emptiers discharge into the various small ponds that are all over the city. The community is rather diverse with many people having migrated just recently. It consists of mostly Hindus with very few Muslims and Christians. People are generally in favour of upgrading the sanitation system to get better FSM services. There are no FSM policies yet, however they are being developed. Therefore, FSM will be recognized as an acceptable solution just like sewered sanitation solution in the near future.

Tasks

Based on the case study on Faekonia provided above, please answer the following questions.

1. It is important to compile the existing information and identify knowledge gaps when carrying out an assessment study.
   a) What secondary data is available in the text?
   b) Where can you collect secondary data?
   c) Make a SWOT of the enabling environment in general for all six parts of the enabling environment.
2. How would you collect primary data? List different methods you would use in order to analyse the situation. Give a method for each of the different stakeholders and list the two most important questions to ask each of them in the context of Faekonia.

Stakeholder	Method	Questions

3. Mention two ways of collecting additional data that cannot be collected through stakeholders.
4. How would you communicate your data? For each of the different stakeholders list one way of displaying and communicating your data.

Stakeholder	Method

Chapter 5.1

Anaerobic digestion

Miriam Englund and Linda Strande

Learning objectives

- Discuss the methane potential of faecal sludge
- Understand concerns about centralized treatment
- Understand the design of community-scale anaerobic digestion

Textbook

Available at www.sandec.ch/fsm_book

- Strande, L., Ronteltap, M. and Brdjanovic, D. (2014). *Faecal Sludge Management - Systems Approach for Implementation and Operation.*

Free online courses (MOOCs)

Available at www.eawag.ch/mooc

- *Introduction to Faecal Sludge Management.* MOOC series by Eawag and EPFL. Module ´Innovations in anaerobic digestion´.
- *Municipal Solid Waste Management in Developing Countries.* MOOC series by Eawag and EPFL. Week ´Organic waste treatment´.

Further Eawag-Sandec publications

- Tilley, E., Ulrich, L., Lüthi, C., Reymond, P. and Zurbrügg, C. (2014). *Compendium of Sanitation Systems and Technologies.* 2nd edition. Dübendorf, Switzerland: Eawag - Swiss Federal Institute of Aquatic Science and Technology www.sandec.ch/compendium
- Lohri, C.R., Vögeli, Y., Oppliger, A., Mardini, R., Giusti, A. and Zurbrügg, C. (2010). *Evaluation of Biogas Sanitation Systems in Nepalese Prisons*. IWA-DEWATS Conference, Switzerland: Eawag - Swiss Federal Institute of Aquatic Science and Technology.
- Vögeli, Y., Lohri, C.R., Gallardo, A., Diener, S. and Zurbrügg, C. (2014). *Anaerobic digestion of biowaste in developing countries. Practical information and case studies.* Dübendorf, Switzerland: Eawag - Swiss Federal Institute of Aquatic Science and Technology.

Additional resources

- Arthur, R. and Hammond, A.B. (2010). *Potential Biogas Production from Sewage Sludge: A Case Study of the Sewage Treatment Plant at Kwame Nkarumah University of Science and Technology, Ghana.* International Journal of Energy and Environment 1(6), pp.1009-1016.

- Drosg, B., Braun, R., Bochmann, G. and Al Saedi, T. (2013). *Chapter 3 - Analysis and characterisation of biogas feedstocks, in:* Wellinger, A., Murphy, J. and Baxter, D. (eds.), The Biogas Handbook. Woodhead Publishing.
- Metcalf & Eddy (2014). *Wastewater Engineering: Treatment and Resource Recovery.* 5th Edition, McGraw-Hill, New York.
- Rose, C. (2015). *Developing a nutrient recovery process for recovering nutrients in anaerobic digestate in low income countries.* Cranfield Water Science Institute.
- Song, Z., Qin, J., Yang, G., Feng, Y. and Ren, G. (2012*). Effect of human excreta mixture on biogas production.* Advanced Materials Research 347, pp. 2570-2575.
- Von Sperling, M. and de Lemos Chernicharo Augustos C. (2005). *Biological Wastewater Treatment in Warm Climate Regions.*

Introduction

The main treatment objective of anaerobic digestion with faecal sludge is stabilization, which is obtained by a microbiological process whereby organic matter is decomposed in the absence of oxygen. Anaerobic digestion systems for faecal sludge can be divided into three groups: low, medium and high levels of complexity, based on their size, the degree of centralization, and the required management level and operational skills. Examples of high-complexity anaerobic digestion systems are the digesters commonly found at large centralized wastewater treatment plants for the treatment of activated wastewater sludge. They require high management and operational skills. To date, these digesters have not been widely used for faecal sludge treatment. In contrast, medium-complexity digestion systems are decentralized reactors that are not fully optimized for operational parameters or treatment performance, so they require less operation and maintenance capacity. An example of this type of digester is the BORDA community-scale reactor. The low-complexity digesters are typically the rural, household-level digesters, which are small, passive systems, mainly for manure and food waste with some co-treatment of faecal sludge. Although the use of this last type of system is common in India and China, it is not applicable in dense urban or peri-urban areas due to lack of space, and so is not covered here.

This chapter focuses on examples of medium-complexity digesters, because at the present time, this is where there is existing operating experience. Most of these current examples represent wet, continuous, mesophilic one-stage reactor systems. The mesophilic system (i.e. a temperature of 25-40°C) is more resistant to operational challenges than the thermophilic (i.e. 55-65°C). In contrast to high-complexity digesters, mixers are not incorporated in medium-complexity digesters. Therefore, there is a loading rate (e.g. total organics, total solids, or volumetric), a solids retention time (SRT) and a hydraulic retention time (HRT). All three are important design parameters in anaerobic digestion, but are not yet well established and further research is required to develop guidelines adapted to the use of faecal sludge as a substrate. According to Vögeli *et al.* (2014), an anaerobic digester fed with organic waste (Municipal Solid Waste) has a hydraulic retention time of 10 to 40 days, and organic loading rates of 2 kg VS/m^3. As seen in Figure 5.1.1, feedstock enters the reactor, and mixes with the material already in the reactor undergoing digestion. Biogas is generated in the slurry through anaerobic digestion. The gas bubbles up to the top part of the reactor where gas accumulates and starts to build up pressure. When the valve is closed, the gas pressure will increase, pushing down the slurry in the reactor into the overflow chamber. It is important to note, that with mesophilic digestion pathogen inactivation is not fully achieved, and the slurry requires further treatment prior to enduse.

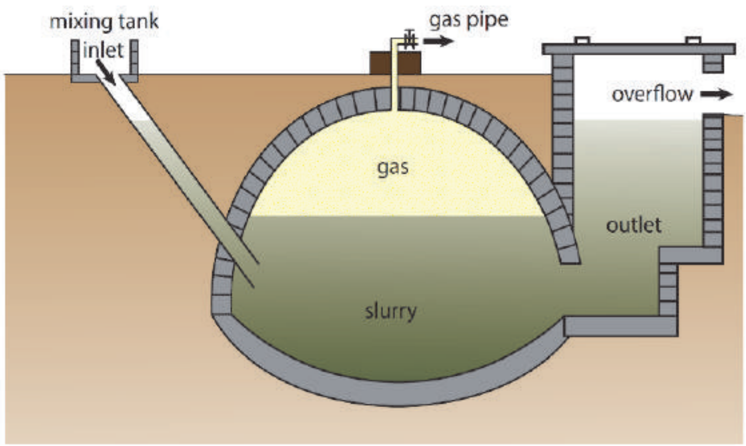


Figure 5.1.1 Illustration of a wet-continuous-mesophilic fixed-dome reactor (taken from the MOOC series Municipal Solid Waste Management in Developing Countries by Eawag and EPFL).

Prior to the design of anaerobic digesters, the biodegradable organic fraction (VS:COD) and its biomethane potential should be determined by a bench-scale test see Example 5.1.1. Theoretically, sludge with very short retention times in containment, such as many public or restaurant toilets, should have higher methane potential than sludge that has for example been sitting in a septic tank undergoing digestion for ten years. However, in reality this theory should not be overstated, as biomethane potential results also include inhibitory factors (e.g. high NH_3). On the other hand, BMP tests in Hanoi still produced reasonable gas with 10-year-old septic tank sludge. Nevertheless, the variability of faecal sludge makes the design difficult and further research is required to establish operational measures, technologies and methods to account for the variability. One BMP value from research with faecal sludge from pit latrines showed an average BMP value of 50.6±19.4 mL/g VS, compared to primary sludge from a wastewater treatment plant with a BMP value of 358.4 mL/g VS (Rose, 2015).

It is important to keep a C:N ratio within a range of 20:1-30:1, and a pH within 6.5-8.2 during operation. Therefore, co-digestion is a feasible way forward. Faecal sludge can be co-digested with other organic waste streams such as brewery waste, spent grain, market waste, or primary sludge. This could increase the digestion and reduce variability.

Faecal sludge as a feedstock

Considerations when using faecal sludge as a feedstock for anaerobic digestion are:

- Digesters are sensitive to upset, and hence require consistent loadings that are conducive to anaerobic digestion, including sufficient temperature, pH and bacterial communities.
- Faecal sludge is highly variable with different organic and volume loadings, and levels of stabilization or degradability.
- It is tricky to predict biogas production and BMP tests should be conducted, as there is a lack of reliable data on degradability of faecal sludge.
- Faecal sludge is typically a slurry and small particle sizes are preferred in digesters.

Examples of anaerobic digesters with faecal sludge as a feed

The design of anaerobic digesters is based on faecal sludge degradability, organic loading, temperature at which the process can be operated, and adequate retention times to facilitate the treatment process. Sludge can be loaded directly into anaerobic digesters, in which case the Q&Q method would be most appropriate to establish quantities and qualities, or can be loaded following other technologies. For example, with very dilute faecal sludge, settling-thickening tanks could precede anaerobic digesters. As there is a general lack of detailed operating data from the operation of anaerobic digesters with faecal sludge, precise design guidelines are difficult to recommend. In the future, with increased experience in research and monitoring, guidelines will be improved.

Example 5.1.1 The biomethane potential (BMP) test

To assess the appropriateness of an anaerobic digester as a faecal sludge treatment technology, a BMP test can be used. The outcome of this test is the maximum-produced volume of methane gas per unit of volatile solids (alternatively per unit wet mass, or COD, or total solids - TS). The BMP test is conducted at a laboratory scale and monitors the daily methane production until less than 1% of the total gas production is left, which usually takes around 20-30 days (Drosg *et al.,* 2014). Refer to Drosg *et al.* (2014) *The Biogas Handbook, Chapter 3 – Analysis and characterization of biogas feedstocks* for details on setting up a BMP test.

$$BMP \left[\frac{ml\, CH_4}{g\, VS}\right] = \frac{Volume\, CH_4}{mass\, VS}$$

The BMP value gives a theoretical maximum. Since methane produced under real-time conditions includes design limitations, the real methane yield will be much less than the BMP test. Therefore a pilot-scale digester can be built based on the BMP test data.

Case study 5.1.1 Anaerobic digesters in Nepal

In two prisons located in the Chitwan and Kanchanpur district a 10 m^3 fixed-dome anaerobic digester was constructed in each of the prisons to treat the faecal sludge from the communal toilets that each serve approximately 100 people. As summarized in Table 5.3.1, the two reactors are fed with 564 L and 519 L of faecal sludge and produce 4 m^3 and 5 m^3 biogas per day, with retention times of 13.5 and 14.5 days, respectively (HRT calculation is based on active digester volume of 7.5 m^3). The digesters are operated at mesophilic temperatures, and the slurry inside the digester has an average pH of 7. The domes were constructed 1.5 m underground for temperature control, and no external heating is used. The gas produced from the digesters is used in the prison kitchen for cooking. Operations and maintenance by the detainees have proved very successful, as they are motivated to making it work in order to have hygienic sanitation and fuel for cooking (Vögeli *et al.*, 2014).

The blockages caused by the incoming faecal sludge frequently needed to be resolved by stirring the gravity-separated solid and liquid layers of faecal sludge to allow it to flow into the digester. Internal maintenance executed by the detainees included condense water removal, and gas leakage checks in the kitchen and throughout the pipes (Lohri, 2010).

Table 5.1.1 Illustration of a wet-continuous-mesophilic fixed-dome reactor (taken from the MOOC series Municipal Solid Waste Management in Developing Countries by Eawag and EPFL).

	Digester 1	Digester 2
Tank volume [m^3]	10	10
Number of users [persons]	115	106
Total faeces [kg/d]	46	42
Total flush water [L/d]	345	318
Total urine [L/d]	172.5	159
Total feed [L/d]	564	519
Active slurry volume [L]	7,500	7,500
Hydraulic retention time [d]	13.5	14.5
Gas production [m^3 biogas /day]	4	5

Case study 5.1.2 BORDA community scale anaerobic digesters

Information provided by BORDA

BORDA, together with local partners, has implemented seven community-scale anaerobic digesters for the treatment of faecal sludge in South-Asia and Sub-Saharan Africa.

BORDA has been collecting operational experiences, to improve future designs of digesters. They have highlighted the need for well-defined treatment objectives, and methods to more accurately estimate quantities and qualities of faecal sludge, as important steps for improvement.

For example, a goal of the anaerobic digester in Devanhalli, India was to provide biogas for the operator to cook with. However, following completion and operation, it was observed that the majority of incoming faecal sludge was from single pit latrines with more than 10 years retention time. Consequently, the gas production is very low, and modifications are being considered.

Another example, is the anaerobic digester at Lubhu faecal sludge treatment plant in Nepal. In this case, the characteristics of the faecal sludge were known, and the two fixed dome reactors of 5 m^3 each are providing sufficient gas for the operators to cook with. Lubhu is currently receiving around 6 m^3 faecal sludge (2 trucks) per week. Lessons learned from Lubhu include difficulties in removing the thickened sludge from the main dome of the reactor, due to limited accessibility. To account for this, sludge will be removed by vacuum trucks every fourth month.

Overall, the need for experienced contractors has been identified everywhere, in order to reliably construct an airtight tank. Based on their experience, BORDA has developed construction guidelines for contractors on how to build fixed dome reactors. For further information refer to the MOOC series Municipal Solid Waste Management in Developing Countries, and Introduction to Faecal Sludge Management by Eawag and EPFL, and the BORDA website.

Exercises

1. What is the main treatment objective of anaerobic digestion?
2. What is the major physical parameter to measure during anaerobic digestion and why?
3. Give the four main design parameters to consider when sizing an anaerobic digester for faecal sludge. Also write a sentence on the importance and main function of each parameter.

4. Anaerobic digestion is a common and well-proven technology for organic waste and primary and secondary sludge. Discuss the pros and cons of anaerobic digestion as a faecal sludge treatment technology.
5. In an anaerobic digestion process, the feed was found to contain heavy metals that inhibit the activity of methanogens. Explain what is likely to occur in the reactor.
6. Failures in anaerobic digestion treatment are often caused by a lack of operational support and maintenance. Identify common problems with operation and maintenance and suggest ways to avoid them.
7. How can the organic loading rate influence the pH and how can this influence methane production?
8. During anaerobic digestion, part of the organic matter is converted into biogas and the outgoing sludge is referred to as digestate. Give an example of end-use for the digestate, also include suggestions on further treatment options if required prior to end-use.
9. What are the potential measures to reduce the impact of variability of faecal sludge feedstock on digester operation?
10. A bio-methane potential (BMP) test should be conducted prior to design of an anaerobic digester. What is a BMP test and what conclusions can you draw based on the BMP test?
11. You are working as a plant engineer at a faecal sludge treatment plant; your boss tells you that they want to change the operation from mesophilic to thermophilic temperatures.
    a) List the pros and cons of thermophilic digestion.
    b) Discuss the challenges of ***operating*** thermophilic temperatures on faecal sludge treatment.
12. The total organic carbon concentration of septic tank sludge is 5,000 mg/L. What is the preferred nitrogen concentration range if the sludge is to be used for digestion?
13. You are working as a plant operator and one of your daily duties is to ensure that gas production is stable. This time, you see that gas production has decreased significantly.
    a) Give three potential reasons for the decreased gas production.
    b) Choose one of the three reasons and explain how you will correct it

Design and calculate

14. Anaerobic digesters can be successfully used on different complexity levels of implementation. Extra benefits are the products which are the gas, that potentially could be used to produce electricity, and outgoing digestate which could after further treatment be used as a soil amendment. To reach this point there are several necessary steps: correct design, an operation and maintenance plan and of course a secure supply of feedstock that can result in methanogenic bacteria growth.
    a) What are the three levels of complexity of faecal sludge anaerobic digestion systems, and by which criteria are they differentiated?
    b) Find three key arguments each, for an anaerobic digester with a medium complexity of implementation and an anaerobic digester with a high complexity of implementation.
    c) Identify what is needed to make the treatment successful, include key operation and maintenance procedures. Highlight how you can monitor the treatment performance.

15. You have been asked to design an anaerobic digester since there is a need for more faecal sludge treatment capacity in a neighbourhood in your city. The idea of an anaerobic digester came from the government. They have identified a demand for cooking fuel in a small city in Bangladesh. You got funding to conduct a pre-study of faecal sludge quantities and qualities and a BMP test in the city. The relevant results from the pre-study are found in the table.

Use the data from the table and

a) Calculate the methane potential
b) Make calculations and decide if the incoming faecal sludge is enough to serve the neighbourhood with cooking fuel. Use the BMP test result in a).

Parameter	Result
Households	100 households
Expected faecal sludge discharge at the treatment plant	10 m^3 FS/day
Faecal sludge TS	8 g TS/L FS
Faecal sludge VS	4.1 g VS/L FS
CH_4	282.9 mL CH_4/L FS
Cooking fuel demand	900 CH_4/household per day

16. The bio-methane potential (BMP) test defines the relation between the volume of methane that can be extracted per mass of degradable matter. Common units are litres of CH_4 per g of TS, VS or COD. How would you compare the units and what could be the differences between them?

17. You are an engineer, designing an anaerobic digester system in Nepal. How many people would your digester need to serve in order to produce enough biogas to power an industrial burner for 8 hours/day? Use data from the digester in table 5.1.2.

Table 5.1.2 Biogas applications and their gas consumption rate (Vögeli *et al.,* 2014).

Biogas application	Consumption rate [L/h]
Household cooking stove	200 – 450
Industrial burner	1,000 – 3,000
Gas lamp, equivalent to 60 W bulb	120 – 150
Generation of 1 kWh of electricity with biogas/diesel mixture	700
Digester	**Values**
Tank volume [m^3]	10
Number of users [cap]	115
Total faeces [kg/d]	46
Total flush water [L/d]	345
Total urine [L/d]	172.5
Total feed [L/d]	564
Active slurry volume [L]	7,500
Hydraulic retention time [d]	13.5
Gas production [m^3 biogas /day]	4

18. Based on data from the digester in the table, what tank volume is required to fuel cooking stoves for a neighbourhood of 10,000 people? Assume that a cooking stove consumes 200-450 L gas per hour and that a household consists of six people using the cooking stove for 3 hours a day.

Digester	Value
Tank volume [m^3]	10
Number of users [cap]	106
Total faeces [kg/d]	42
Total flush water [L/d]	318
Total urine [L/d]	159
Total feed [L/d]	519
Active slurry volume [L]	7,500
Hydraulic retention time [d]	14.5
Total gas production [m^3 biogas /day]	5

19. The hydraulic retention time is the average time the digestate stays in the reactor. Anaerobic digesters for organic waste in tropical climates usually have a hydraulic retention time of about 30 days. If you have a treatment system receiving approximately 5 m^3 faecal sludge every week, what tank volume must the digester have to keep a hydraulic retention time of 30 days? Why do we use a hydraulic retention time and what is the biggest influence on the hydraulic retention time?

Chapter 5.2

Conditioning

BJ Ward and Linda Strande

Learning objectives

- Explain conditioning
- Name types of conditioners
- Discuss considerations for implementation

Textbook

Available at www.sandec.ch/fsm_book

- Strande, L., Ronteltap, M. and Brdjanovic, D. (2014). *Faecal Sludge Management - Systems Approach for Implementation and Operation.*

Free online course (MOOC)

Available at www.eawag.ch/mooc

- *Introduction to Faecal Sludge Management*. MOOC series by Eawag and EPFL. Module 'Innovations in conditioning'.

Further Eawag-Sandec publications

Available at www.sandec.ch/fsm_tools

- Gold, M., Dayer, P., Faye, M.C.A.S., Clair, G., Seck, A., Niang, S., Morgenroth, M. and Strande, L. (2016). *Locally produced natural conditioners for dewatering of faecal sludge.* Environmental Technology, 37(21), 2802-2814.
- Moto, N., Esanju, M., Andriessen, N., Kimwaga, R. and Strande, L. (2018). *Use of chitosan and Moringa oleifera as conditioners for improved dewatering of faecal sludge*. Proceedings of the 41st WEDC International Conference, Nakuru, Kenya, 9-13 July 2018, Paper 3014, p. 7.
- Ward, B.J., Sam, S., Andriessen, N., Morgenroth, E. and Strande, L. (2018). *Research priorities and progress in faecal sludge dewatering.* Sandec News, 19, 10-11.

Additional resources

- Metcalf & Eddy (2014). Wastewater Engineering: Treatment and Resource Recovery. 5th edition, McGraw-Hill, New York.
- Reynolds, T.D. & Richards, P.A. (1996). *Unit operations and processes in environmental engineering* (Vol. 20). PWS Publishing Company, Boston, MA.
- SNF Floerger (2003). Sludge dewatering. Brochure Water Treatment–Tech 3 E. Available at https://www.snf.us/wp-content/uploads/2014/08/Sludge-Dewatering-E.pdf.

- Tayler, K. (2018). *Faecal Sludge and Septage Treatment: A guide for low-and middle-income countries*. Practical Action Publishing.
- MICRODYN NADIR (2017). Technical Service Guide - Troubleshooting Jar Testing Procedure. Form No: TSG-T-008. Revision: B. Date: May 25, 2017. Available at https://static1.squarespace.com/static/54e2b7aee4b0902efd671f90/t/5bb672650d92975174ce3260/1538683493717/TSG-T-008+Jar+Testing+Procedure+RevB.pdf.

Introduction

Conditioning is the addition of chemicals (conditioners) to sludge in order to improve dewatering and settling performance, and it can be considered a transferring technology from wastewater treatment. Conditioners are mixed with faecal sludge prior to solid-liquid separation. The use of conditioners can make dewatering on drying beds faster or improve effluent quality from settling-thickening tanks, but they are not necessary for these technologies to function. Conditioners can also enable the use of innovative and transferring low-footprint dewatering technologies such as geotubes (geotextile bags) and mechanical dewatering units that take up less space than established faecal sludge dewatering technologies. These technologies will not work without the addition of conditioners, which is a barrier to implementing them for faecal sludge treatment at full scale. Because each batch of faecal sludge that arrives for treatment is highly variable in terms of its physical-chemical characteristics, determining how much and which type of conditioner to add is not clear. Accurate dosing would require time-intensive laboratory tests for each new batch of sludge. Improved methods for selecting optimal conditioner doses are the focus of current research, and may help advance the adoption of conditioners for innovative and transferring dewatering technologies.

Types and mechanisms of conditioners

Conditioners can be inorganic chemicals such as lime, ferric chloride, and aluminum sulfate, or they can be charged polymers ('polyelectrolytes'). Polymers can be locally produced from natural materials, such as chitosan or *Moringa oleifera*, or can be proprietary materials sourced from chemical companies. It is expected that cationic (positively charged) polyelectrolytes will work best with faecal sludge, as they will be more likely to interact with organic particles, which are negatively charged.

Conditioners work by destabilizing small suspended particles to form larger aggregates (shown in Figure 5.2.1). This happens through coagulation, which is the initial destabilization and aggregation of colloidal particles. This is followed by flocculation, which is the formation of larger particles, or 'flocs', from smaller particles.

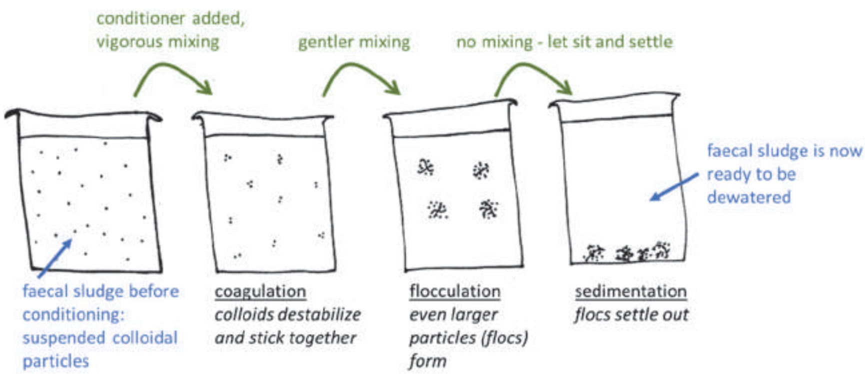


Figure 5.2.1 Steps of faecal sludge conditioning, coagulation, flocculation, and sedimentation.

Selection of conditioners and optimal dose

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

Faecal sludge properties: Conditioners are commonly dosed as a function of the total solids. Other factors such as the electrical conductivity or the degree of stabilization may influence which type of conditioners work best.

Dewatering technology: Conditioners need to be compatible with the technologies used for dewatering. For example, centrifuge dewatering requires conditioning with polymers that produce flocs that are resistant to high shear (i.e. very high molecular weight, and usually branched or structured polymers).

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

Laboratory testing, pilot-scale to full-scale

In comparison to wastewater sludge, there is hardly any experience available of faecal sludge conditioning. Conditioners have mostly been used with faecal sludge on a laboratory- and pilot-scale. In the laboratory, conditioner performance and dose is determined using jar tests, where faecal sludge is mixed with different doses or different types of conditioner. After mixing, the settling and/or dewatering performance of the conditioned faecal sludge is compared to the unconditioned faecal sludge. The settling performance is measured using

Imhoff cones. Often, the sludge volume index (SVI) and/or the COD and/or TSS in the supernatant after settling are used as indicators for the settling performance. The dewatering time is measured using the capillary suction time (CST) or specific resistance to filtration (SRF). Dewatered cake dryness is measured by dewatering using centrifugation or a lab-scale filter press. Dry solids in the dewatered sludge cake are measured and compared. At the pilot-scale, similar experiments can be conducted with settling-thickening columns or pilot-scale drying beds.

To transfer the use of conditioners to faecal sludge at full-scale, information from manufacturers and laboratory experiments is required. Scaling up the conditioner use has been difficult, as the dose and the selection of the conditioner are currently determined with laboratory tests. Since faecal sludge is highly variable, it is unfeasible to perform time-intensive laboratory tests on each individual batch of faecal sludge. Current research is focused on developing a way to predict the conditioner dose from rapid online measurements of the influent faecal sludge. In addition to identifying the optimal conditioner dose and achieving the desired dewatering performance, the cost, availability/supply chain, and chemical safety are important considerations for the implementation of conditioners in faecal sludge. Additional infrastructure may be required to use conditioners, including a tank for storage, a dosage device, and a homogenization tank for mixing.

Step-by-step approach for design of faecal sludge conditioning protocol

The approach taken here for the selection of the best conditioner and optimal dose is summarized in Table 5.2.1.

Table 5.2.1 Step-by-step approach for design of faecal sludge conditioning protocol.

Step 1	Identify target solid-liquid separation technology
Step 2	Select potential conditioners
Step 3	Identify lab-scale metrics for performance
Step 4	Test conditioner types and doses at lab-scale
Step 5	Select best conditioner and optimal dose
Step 6	Apply conditioner to faecal sludge at pilot-scale

Step 1: Identify target solid-liquid separation technology

The selection of a conditioner is partly based on the solid-liquid separation technology. These technologies include:

- Settling-thickening tanks or Imhoff tanks
- Unplanted drying beds
- Geotubes (geotextile bags)
- Mechanical filter presses
- Mechanical screw presses
- Centrifuges

Step 2: Select potential conditioners

An appropriate conditioner must:

- Work with the selected solid-liquid separation technology, as discussed in SNF Floerger (2003)
- Be locally available
- Be affordable.

Step 3: Identify laboratory-scale metrics for performance

This depends on the selected solid-liquid separation technology and the desired treatment outcomes, see Table 5.2.2.

Table 5.2.2 A summary table of the required lab-scale metrics for the respective solid-liquid separation technology and its desired treatment outcome.

Technology	Desired treatment outcome	Lab-scale metric
Settling-thickening tanks or Imhoff tanks	Clear, clean supernatant	COD, TSS, or turbidity of supernatant after settling in Imhoff cones
	Compact sludge blanket	SVI
	Fast settling	Change in SVI and/or COD, TSS, or turbidity of supernatant over a range of settling times
Unplanted drying beds Geotubes (geotextile bags) Mechanical filter presses Mechanical screw presses Centrifuges	Clear, clean effluent	COD, TSS, or turbidity of effluent, measured in a comparable lab-scale system*
	High solids concentration in dewatered sludge	Dry solids in sludge cake
	Fast dewatering	Amount of time it takes for water to filter through sludge cake (measured by CST or SRF), or amount of time for sludge to reach a specific dryness, measured in a comparable lab-scale system*

(*) Comparable laboratory-scale system examples: a CST machine can be used to estimate the 'filtration time' or 'filterability' of faecal sludge in systems that use filtration mechanisms to dewater e.g. unplanted drying beds, geotextile bags, mechanical filter presses. The more technology-specific the laboratory-scale measurement, the more likely that it is a good predictor of pilot- and full-scale performance. For example, filters made from the same geotextile material as geotextile bags will be better predictors of geotextile performance than CST, and bench-scale filter presses using the same pressure settings and membrane filters will be better predictors of the full-scale filter press performance.

Step 4: Test conditioner types and doses at lab-scale

Perform a jar test to determine the optimum doses and conditioner type (adapted from MICRODYN NADIR, 2017):

1. Mix stock solutions of the conditioners.
2. Homogenize the faecal sludge by stirring with a spoon or gentle shaking, and use a graduated cylinder to measure out test volumes into jar test beakers.
3. Using the prepared stock solution of conditioner, dose each beaker with increasing amounts of the conditioner. Leave one beaker as a control with no conditioner added.
4. After dosing the beakers, turn on the stirrers, or stir the beakers by hand. Stir at a speed setting that mimics the desired treatment plant operation. For example, in the faecal sludge treatment plant, aluminum sulphate is added followed by static mixing, then flocculation happens for 30 minutes, and then all is left to settle for 90 minutes. The jar test should mimic this process by starting with aluminum sulfate addition and high rpm mixing, followed by 30 minutes of reduced speed mixing to match the flocculator conditions, and then the stirrers should be turned off and the mixtures left to settle for 90 minutes.
5. Observe the beakers after the jar test is completed. It can often be observed, just by looking at the jars, whether the conditioner is under- or overdosed. Under-dosed faecal sludge looks cloudy and turbid. Over-dosed faecal sludge may appear bubbly/soapy/foamy and can also be turbid. Optimal doses should yield dense flocs that settle to the bottom of the beaker, and clear supernatant. Measure the relevant lab-scale metrics in each beaker for a quantitative performance analysis.
6. Repeat the jar tests for each conditioner.

Step 5: Select best conditioner and optimal dose

Collect the observations and measurements from the jar tests with different doses and different conditioners. It is helpful to graph the results in order to visualize and compare the performance and infer the trends. Typically, the optimal dose is selected when the performance is >75% reduction of the performance parameter, such as dewatering time or TSS in the supernatant. Sometimes, if there are two treatment goals (e.g. clear effluent and also high dry solids after dewatering), the optimal dose or best conditioner may be different for each treatment goal. In this case, it is useful to consider what parameters would be 'good enough' to achieve the multiple treatment goals. Selecting a conditioner and dose should also be based on how variable the influent sludge characteristics will be. If variability is high, it could make sense to a) select a high dose of a conditioner that does not exhibit overdose behaviour to account for the variability, or b) select a median dose based on the median characteristics, and just accept that dewatering performance will also be variable. Option b may work for established technologies such as settling-thickening tanks and drying beds, but would not work well with filter-based emerging technologies such as geotubes, which are rendered useless if clogged by poorly conditioned sludge. If immediate implementation of conditioners is desired, select a conditioner that will be the most robust for the context.

Step 6: Apply conditioner to faecal sludge at pilot-scale

Apply the selected conditioner at the selected dose at the pilot-scale. Monitor the same performance metrics and verify the conditioner performance. One important caveat is that using conditioners at a larger scale, especially with mechanical dewatering or geotubes, comes with the increased risk that comes from adopting transferring or innovative technologies. This risk would need to be managed appropriately, perhaps with partnerships with research institutions or with public-private partnerships.

Example 5.2.1

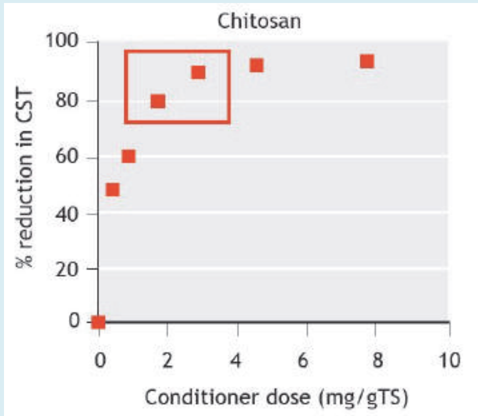
Naturally available conditioners, chitosan and *Moringa oleifera*, have been tested in combination with unplanted drying beds using a laboratory test and a pilot-scale drying bed test facility. Chitosan costs 15 US$/kg and *Moringa oleifera* costs 30 US$/kg.

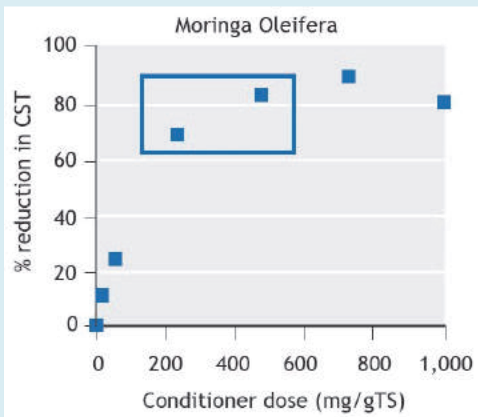
To determine optimal doses of chitosan and *M. oleifera*, jar tests are performed with the following concentrations of conditioners, and capillary suction time (CST) measured as an approximation of dewatering time, yielding the following results:

Conditioner	Dose [mg/g TS]	% reduction in CST
Chitosan	0	0
	0.5	45
	1	60
	2	79
	3	88
	5	90
	8	92
Moringa oleifera	0	0
	10	13
	50	25
	100	33
	250	68
	500	83
	750	87
	1,000	80

Typically, the optimal dose is selected when performance is >75% reduction of the dewatering time or TSS in the supernatant. The optimal dose of chitosan is approximately 2-3 mg/g TS, and the optimal dose of *Moringa oleifera* is approximately 250-500 mg/g TS for the faecal sludge samples tested.

Which conditioner would be best to choose for the scale-up? Both can achieve a similar performance in terms of CST reduction, but optimal doses required to achieve this are very different. Conditioners can be compared by calculating the cost to condition 1 tonne of faecal sludge (FS) (assume 1% TS).





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$$\text{for } \frac{1{,}000 \text{ kg FS}}{1 \text{ tonne FS}} \times \frac{1 \text{ kg TS}}{100 \text{ kg FS}} = 10 \text{ kg TS to condition in 1 tonne FS}$$

Chitosan:

Optimal dose $= 2.5 \frac{\text{mg}}{\text{g TS}} = 2.5 \frac{\text{g}}{\text{kg TS}}$

$$10 \text{ kg TS } \times \frac{2.5 \text{ g chitosan}}{1 \text{ kg TS}} = 25 \text{ g chitosan} = 0.025 \text{ kg chitosan}$$

$$0.025 \text{ kg chitosan } \times \frac{15 \text{ US\$}}{\text{kg chitosan}}$$

$= 0.38$ US$ to condition 1 tonne of FS with chitosan

***Moringa oleifera*:**

Optimal dose $= 375 \frac{\text{mg}}{\text{g TS}} = 375 \frac{\text{g}}{\text{kg TS}}$

$$10 \text{ kg TS } \times \frac{375 \text{ g M. oleifera}}{1 \text{ kg TS}} = 3{,}750 \text{ g M. oleifera} = 3.75 \text{ kg M. oleifera}$$

$$3.75 \text{ kg M. oleifera} \times \frac{30 \text{ US\$}}{\text{kg M. oleifera}}$$

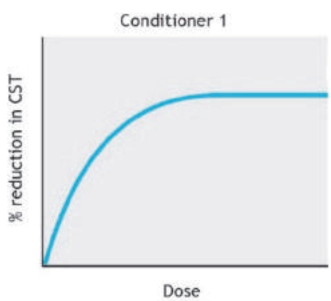
$= 112.5$ US$ to condition 1 tonne of FS with M. oleifera

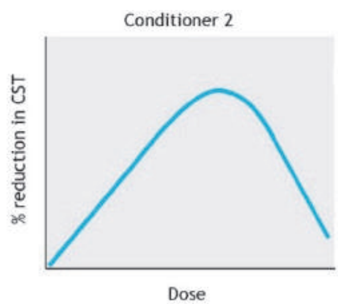
By calculating the costs, in this example chitosan is clearly more economical to use for conditioning faecal sludge than *Moringa oleifera*. Before making a final decision about the conditioner dose and selection, a risk-based management approach should be considered, including partnership with a research institute, and a risk-management strategy should be adopted to ensure that there would be no decline in faecal sludge treatment quality if conditioners did not function well at full-scale.

Exercises

1. What is/are the treatment objective(s) of conditioning?
2. Why does unconditioned faecal sludge not work with dewatering technologies such as filter presses (transferring) and geotubes (innovative)?
3. How can you determine the optimal conditioner dose for faecal sludge?
4. Which faecal sludge would you expect to require a higher conditioner dose: unstabilized faecal sludge from a public toilet cesspit, or relatively stabilized faecal sludge from a household septic tank?
5. Name two inorganic conditioners and two polyelectrolyte conditioners. How are these two types of chemicals different from one another? How are these two types of chemicals the same?
6. When would it be inappropriate to use conditioners to aid faecal sludge dewatering?

7. How would you expect the addition of a polymer conditioner (at the optimal dose) to impact the COD in the supernatant after settling for 30 minutes compared to unconditioned faecal sludge?
8. What would you do differently to determine the optimal conditioner dose in the laboratory, depending on whether you were interested in improving the settling-thickening performance or the dewatering speed on the drying beds?
9. Presented below are the results of jar tests for two different conditioners. You are operating a full-scale faecal sludge treatment plant with limited capacity and resources for determining the optimal conditioner dose for every new batch of faecal sludge. Which conditioner would you select and why?





10. Presented below is data collected from jar tests conditioning faecal sludge with chitosan, lime, and commercial cationic polymer flocculant, along with price data for each conditioner.

Conditioner	Conditioner cost [US$/kg]	Dose [mg/g TS]	SRF [x10^{12} m/kg]	TSS in supernatant [g/L]
Chitosan	20	0	42.8	3.6
		0.5	38	2.5
		1	36.8	1.7
		2	25.7	0.9
		3	13.8	0.5
		5	2.1	0.2
		8	1.9	0.07
		15	6.8	1.3
Lime	0.15	0	42.8	3.6
		1	18.4	2.1
		3	6.8	0.7
		5	2.3	0.3
		10	1.9	0.2
		15	1.9	0.08
		25	1.9	0.08
Commercial cationic polymer flocculant	2.6	0	42.8	3.6
		0.05	30.7	2.8
		0.1	15.9	0.8
		0.25	7.8	0.3
		0.5	0.6	0.01
		0.75	0.2	0.02
		1	3.9	0.3
		1.25	10.9	0.8

a) Calculate the optimal dose for each conditioner in terms of
   - Standard resistance to filtration (SRF)
   - Supernatant TSS reduction

Use the following equation to calculate the optimal dosage, remembering that the optimal dosage is usually based on > 75% reduction.

$$\% \text{ reduction} = \frac{\text{SRF/TSS}_{\text{unconditioned}} - \text{SRF/TSS}_{\text{dose}}}{\text{SRF/TSS}_{\text{unconditioned}}} \times 100\%$$

b) If your treatment goal is to reduce the dewatering time on drying beds, which conditioner(s) would you select to further test at the pilot-scale, based on cost and performance?

Chapter 5.3

Solid fuels from faecal sludge

Nienke Andriessen and Linda Strande

Learning objectives

- Describe treatment products that can be used as a solid fuel
- Name characteristics that are relevant to assess the potential as solid fuels
- Discuss considerations for implementation

Textbook

Available at www.sandec.ch/fsm_book

- Strande, L., Ronteltap, M. and Brdjanovic, D. (2014). *Faecal Sludge Management - Systems Approach for Implementation and Operation.*

Free online course (MOOC)

Available at www.eawag.ch/mooc

- *Introduction to Faecal Sludge Management.* MOOC series by Eawag and EPFL. Module ´Innovations in solid fuels´.

Further Eawag-Sandec publications

Available at www.sandec.ch/fsm_tools

- Andriessen, N., Ward, B.J. and Strande, L. (2019). *To char or not to char? Review of technologies to produce solid fuels for resource recovery from faecal sludge.* Journal of Water Sanitation and Hygiene for Development.
- Gold, M., Ddiba, D.I.W., Seck, A., Sekigongo, P., Diene, A., Diaw, S., Niang, S., Niwagaba, C.B. and Strande, L. (2017). *Faecal sludge as a solid industrial fuel: a pilot-scale study.* Journal of Water Sanitation and Hygiene for Development, 7(2), 243-251.
- Diener, S., Semiyaga, S., Niwagaba, C.B., Murray Muspratt, A., Gning, J.B., Mbéguéré, M., Ennin, J.E., Zurbrügg, C. and Strande, L. (2014). *A value proposition: Resource recovery from faecal sludge - Can it be the driver for improved sanitation?* Resources, Conservation and Recycling, 88, 32-38.
- Schoebitz, L., Andriessen, N., Bollier, S., Bassan, M., and Strande L. (2016). *Market Driven Approach for Selection of Faecal Sludge Treatment Products.* Eawag-Sandec.
- Ward, B.J., Gold, M., Turyasiima, D., Studer, F., Getkate, W., Maiteki, J.M., Niwagaba, C.B. and Strande, L. (2017). *SEEK (Sludge to Energy Enterprises in Kampala): Co-processing Faecal Sludge for Fuel Production.* 40th WEDC International Conference, Loughborough, UK.

- Murray Muspratt, A., Nakato, T., Niwagaba, C.B., Dione, H., Kang, J., Stupin, L., Regulinski, J., Mbéguéré, M. and Strande, L. (2014). *Fuel potential of faecal sludge: calorific value results from Uganda, Ghana and Senegal.* Journal of Water Sanitation and Hygiene for Development, 4(2).

Additional resources

- Koottatep, T., Fakkaew, K., Tajai, N., Pradeep, S.V. and Polprasert, C. (2016). *Sludge stabilization and energy recovery by hydrothermal carbonization process.* Renewable Energy, 99: 978-985.
- Sanivation & UNHCR (2018). *Container-based Toilets with Solid Fuel Briquettes as a Reuse product.* Best Practice Guidelines for Refugee Camps.
- Septien, S., Singh, A., Mirara, S.W., Teba, L., Velkushanova, K. and Buckley, C.A. (2018). *'LaDePa' Process for the Drying and Pasteurisation of Faecal Sludge from VIP Latrines using Infrared Radiation.* S. African Journal of Chemical Engineering, 25.

Introduction

Research has shown that solid fuels made of faecal sludge are an attractive resource recovery option (Diener *et al.*, 2014).

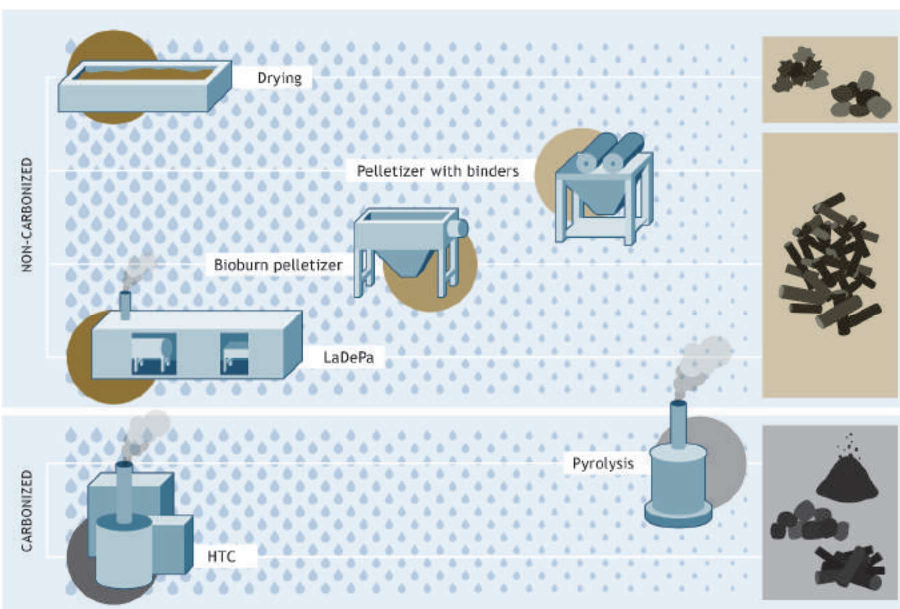


Figure 5.3.1 The various technology options to produce solid fuel from faecal sludge. The figure illustrates the range of required level of dryness of the input sludge, represented by the positioning of the technology icons ranging from 20% dry solids on the left to 90% dry solids on the right, taken from Andriessen *et al.* (2019).

Solid fuel options can be in non-carbonized (dried) or carbonized forms, and these have distinct characteristics and usage properties. Also, for each of the solid fuel producing technologies, different levels of moisture content are required. Dewatering and the ability to dry to the required level of input dryness are important considerations when selecting technologies to produce fuel, as dewatering and drying require varying levels of time and space depending on the technologies used. Figure 5.3.1 provides an overview of the different technologies to produce solid fuel from faecal sludge; the reducing size of the droplets from left to right indicates the level of required dryness for faecal sludge as an input to the technology. For further information in the chapter refer to Andriessen *et al.* (2019).

Non-carbonization technologies

Dried sludge can simply be combusted; ≥90% dryness is a suitable dryness for direct combustion. Passive drying beds are a common way to dry sludge, but to achieve 90% dryness requires both a lot of time as well as an extensive area of land. To improve drying time, active drying methods such as ventilation, thermal drying (supplying heat), solar drying, and mechanical or manual turning can be used, depending on the availability of electricity.

Semi-dried and dried sludge can be compressed into pellet form. Various pelletizing machines exist. Conventional pelletizers require a binder to keep the pellet together. Binders can alter the energy content of a pellet in a positive or negative way. Common binders that can be used with faecal sludge include cassava starch, beeswax, clay, lignosulfonates, and molasses. Relatively dry sludge of ≥70% dryness is needed for conventional pelletizers. Alternative pelletizing machines are the Bioburn pelletizer, and the LaDePa (Latrine Dehydration and Pasteurization) pelletizing process. The Bioburn pelletizer extrudes sludge of 30-60% dryness to form a pellet without the use of a binder. The LaDePa process requires input sludge of 20-30% dryness. The process includes manual removal of large pieces of debris, extrusion to form pellets, drying and then pasteurization of the pellets by infrared radiation, and it produces sanitized pellets. For more information on the LaDePa process, refer to Septien *et al.* (2018).

Carbonization technologies

Pyrolysis is the carbonization of biomass at temperatures between 300-700°C without the presence of oxygen. Pyrolysis produces char, gasses and oil (tar) products, with 70-90% dryness input sludge, which can all be used for further resource recovery. Slow pyrolysis (at heating rates from 1-10°C/min and residence times in the order of hours) is the process that has the highest char yield, and is therefore most suitable for char production as a solid fuel.

Hydrothermal carbonization (HTC) is the thermochemical conversion of biomass at temperatures between 180-250°C for 1-12 hours' reaction time under high pressure (>30 bar). An input dryness of 20% has been found to be optimal for faecal sludge. The high pressure that is needed for HTC can be dangerous if operated by untrained staff. The use of HTC for faecal sludge is still in the research phase.

A char endproduct can be pelletized or turned into briquettes after carbonization to adjust the shape according to the requirements of the enduser.

Relevant parameters

Calorific value

Calorific value, an estimate of the energy content, is an important characterization parameter. The unit of energy content is mega joules per kilogram of 100% dried faecal sludge (MJ/kg). Depending on the faecal sludge characteristics and the treatment technology used, faecal sludge can have a range of calorific values ranging from 8 to 19 MJ/kg dried sludge (Andriessen *et al.*, 2019). Reasons for the range in calorific values include differences in composition in types of organic matter (e.g. volatile solids, fixed carbon) and the high concentrations of inorganic material in the sludge. The conventional method to measure calorific value is using a bomb calorimeter.

Ash

Inorganic material is estimated by the ash content. It is the proportion of fuel that does not burn and therefore does not contribute to the calorific value. Potential contributions to inorganic material come from soil in unlined or partially lined pit latrines, from sand and soil entering the onsite sanitation technology through a drop hole, and from sand from drying beds during treatment. Ways to keep sand out of faecal sludge need to be improved to increase the energy recovery potential of faecal sludge. Carbonization of sludge also increases the ash content by removal of volatile gases. In one study conducted by Sandec and its research partners in Dar es Salaam and Kampala, char produced from dried faecal sludge had calorific values of 7 to 11 MJ/kg dried sludge and ash contents of 55 to 70%. These are high for use as solid fuels considering that, based on the literature, charcoal has a calorific value of 31 to 33 MJ/kg and an ash content below 5%.

Technology selection

To select a suitable technology, the steps in Table 5.3.1 can be followed.

Table 5.3.1 Step-by-step approach for selection of solid fuel production technology.

Step 1	Conduct a market assessment
Step 2	Estimate expected fuel quantity and quality
Step 3	Establish enduser requirements
Step 4	Select technology options

Step 1: Conduct a market assessment

Conduct a market assessment (for more information refer to the Market-Driven Approach (MDA) by Schoebitz *et al.* (2016) and chapter 2.4 in this book) to assess what treatment product has the highest market attractiveness in a particular location. If it is solid fuel, then proceed with the following steps.

Step 2: Estimate expected fuel quantity and quality

The fuel quality will depend on faecal sludge qualities and vary across locations. Generally, faecal sludge that is relatively unstabilized has a higher calorific value. Faecal sludge with a low ash content has a better fuel quality because ash is an inert material, and does not contain any energy. It is important to understand whether the chosen combustion technology is able to deal with the high ash content of faecal sludge. Faecal sludge also contains elements that can produce emissions during carbonization and combustion such as nitrogen and sulphur oxides, particulate matter or black carbon. These can all have negative impacts on the environment and therefore mitigation needs to be considered before implementation. Faecal sludge qualities can be determined in a laboratory. Additionally, make an estimation of what quantities of incoming sludge are expected to see if it is a sufficient amount for the endusers' fuel requirements (see step 3).

Step 3: Establish enduser requirements

The desired solid fuel form is very dependent on the enduser and the type of combustion technology (e.g. furnace, cooking stove). For example, the enduser might want to use char where coal is currently used. The solid fuel can be in the form of powder, pellets, or briquettes. Large industries such as cement or brick companies can be important customers for the use of dried faecal sludge and they can provide a large and consistent revenue stream for treatment operators. These industries can also be better equipped than individual households to deal with environmental measures and safety standards. However, the quantities of fuel that large industries require for full-scale implementation may exceed the quantities of sludge that are currently being treated.

Step 4: Select technology options

The selection of technology will be a trade-off between the financial, technical and social aspects. Compare the technology options based on the available space for drying, energy requirements (and availability), operational capacity requirements, acceptance of the use of a solid fuel produced from faecal sludge, and the environmental impact. Where there is no space at all available for drying, technologies that can deal with relatively wet sludge could be suitable (LaDePa or HTC). A full decision framework for the technology options for solid fuel produced from faecal sludge can be found in Andriessen *et al.* (in press). The final selection of a technology should always be made and verified within the local context, including factors from the enabling environment (e.g. rules and regulations, social preferences, political backing, and available resources). The decision framework presented here is not a standalone tool, and should always be discussed with all the relevant stakeholders.

Case study 5.3.1 Sanivation in Kenya

The start-up company Sanivation is based in Naivasha, Kenya. Their mission is to provide clean, safe and efficient sanitation services for a healthy and dignified life (www.sanivation.com). They provide a (urine-diverting) container-based toilet service and bi-weekly collection of the contents. The faecal matter is brought to a treatment plant, where it is dried and then transformed into solid fuel briquettes (Figure 5.3.2).

Figure 5.3.2 The Sanivation system overview (Sanivation & UNHCR, 2018).

In the refugee camp in Kakuma, Kenya, Sanivation has collaborated with UNHCR to provide sanitation and valorisation of faecal sludge (Sanivation & UNHCR, 2018). The source-separated faeces comes from containers that are distributed to households in the camp. The customers/endusers of the solid fuel product are households. Producing a solid fuel for households requires a high level of pathogen inactivation, and thus solid fuel technologies that can ensure a sanitized, pathogen-free endproduct are suitable (e.g. HTC, pyrolysis or the LaDePa).

Figure 5.3.3 Workers at the Sanivation plant in Naivasha putting the briquettes on drying racks to dry (photo: Sanivation).

In a refugee camp setting, low-tech processes that consume no or limited electricity are preferred. In this case, the incoming faeces comes from container-based sanitation systems where faeces and urine were separated at source. Source-separated faeces commonly has a lower ash content and a higher calorific value than faecal sludge that has been stored in onsite sanitation systems (Andriessen *et al.*, 2019). Sanivation inactivates pathogens in the faeces with a solar thermal treatment system at 65°C. The dried faeces is then used as a binder (with water) to produce briquettes with charcoal dust, which is also a waste product that is available in the camp. Further drying is done on drying racks. Charcoal dust has a high calorific value, and can thus help to improve the quality of the briquettes. The resulting briquettes are on average 22 MJ/kg. Other (carbonized) biowaste streams can also be used for manufacturing briquettes.

Exercises

1. Which of the following treatment products can be used as a solid fuel?
   a) Biogas
   b) Dewatered faecal sludge
   c) Dried faecal sludge
2. Name two benefits of solid fuel from faecal sludge as a resource recovery option.
3. Who could be the endusers of faecal sludge solid fuels?
4. Explain in your own words what carbonization is.
5. What is the biggest challenge of carbonized faecal sludge?
6. Which technologies could be suitable when there is no space available for drying?
7. You want to produce a solid fuel from faecal sludge with a calorific value of 14 MJ/kg and an ash content of 22%. Your engineer proposes to dry the sludge with a solar drying system (unplanted drying beds with greenhouses and a fan to distribute the warm air) and then pelletize the dry sludge.
   a) Do you agree with her? Why (not)?
   b) What information is missing to make a more informed decision?
8. The mayor of a neighbouring city sees the positive results of producing solid fuel from faecal sludge in your city, and wants to implement the same system. The faecal sludge has a calorific value of 11 MJ/kg and an ash content of 52%. Do you think the mayor should implement the same system? If not, could you propose another solution (based on the information provided)?
9. During the raining season, the incoming sludge is more dilute (3% dryness). Knowing this, what would you change in the treatment system: unplanted drying beds with greenhouses and a fan to distribute the warm air followed by pelletizing of the dry sludge?

10. Consider faecal sludge with the following characteristics:

-	Dryness	30%
-	Calorific value	16.1 MJ/kg
-	Ash content	39%

The enduser requires a powdery fuel for combustion in kilns. What solid-fuel producing technology would you choose and why?

11. Consider faecal sludge with the following characteristics:

-	Dryness	11%
-	Calorific value	17 MJ/kg
-	Ash content	31%

The endusers are households that are sceptical of using a faecal sludge product. They are currently using charcoal to cook with. Two engineers are arguing about whether a solid fuel made of faecal sludge is appropriate or not.

a) What social (behaviour change) solutions might be required?

b) What solid-fuel producing technology would you choose and why?

Chapter 5.4

Vermi and fly larvae treatment

Miriam Englund, Moritz Gold and Linda Strande

Learning objectives

- Explain the treatment processes and operation
- Understand the advantages and disadvantages compared to co-composting
- Discuss considerations for implementation

Textbook

Available at www.sandec.ch/fsm_book

- Strande, L., Ronteltap, M. and Brdjanovic, D. (2014). *Faecal Sludge Management - Systems Approach for Implementation and Operation*.

Free online course (MOOC)

Available at www.eawag.ch/mooc

- *Introduction to Faecal Sludge Management.* MOOC series by Eawag and EPFL. Module ´Innovations in vermi and fly larvae composting´.

Further Eawag-Sandec publications

Available at www.sandec.ch

- Diener, S., Zurbrügg, C. and Tockner, K. (2009). *Conversion of organic material by black soldier fly larvae: establishing optimal feeding rates.* Waste Management and Research, 27(6), 603-610.
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Additional resources

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Introduction

Vermi and fly larvae treatment can be considered an innovative technology, or a transferring technology from the treatment of biowastes, wastewater sludge (biosolids), and animal manures. One challenge of vermi and fly larvae treatment is the potentially high ammonia concentrations of faecal sludge that are toxic to worms and larvae. The current state of knowledge for vermi and fly larvae treatment of faecal sludge is limited to a few laboratory-scale, bench-scale, and pilot-scale studies. Treatment at the household level has also been implemented with urine-diverting vermicomposting toilets (Lalander *et al.,* 2013a), but this is not discussed in this chapter.

The treatment objectives of vermi and fly larvae treatment are sludge stabilization and nutrient management. Some pathogen inactivation has been observed during vermi and fly larvae treatment. However, pathogen inactivation is not reliably or consistently achieved with vermi and fly larvae treatment, and final products should still be considered to contain human and animal pathogens. Therefore, the endproducts need to be processed accordingly depending on the intended use in order to protect public health (Gold *et al.,* 2018). For example, a small-scale black soldier fly larvae company in Kenya boils and sun-dries larvae before enduse to inactivate pathogens.

Vermi treatment consists of either vermicompost or vermifilters. Vermifilters are soil filters that include worms that are fed with faecal sludge without prior treatment (Furlong *et al.*, 2015). The solids accumulate on top of the filter while the liquids pass through the filter to the bottom. This chapter focuses on vermicomposting. Fly larvae treatment typically consists of either black soldier fly larvae (*Hermetia illucens*) or housefly larvae *(Musca domestica).* This chapter focuses on black soldier flies (BSF), which are most commonly used (Dortmans *et al.*, 2017).

Vermicomposting

In vermicomposting, worms are nursed in bins together with bedding material and a feed source. Vermicomposting is commonly operated in batch or semi-batch modes, but flow-throw systems are possible. Bedding material is an important design consideration, as worms cannot live in the feed material. The feed passes through the worm's digestive system, and the residue of the digestion is excreted as a solid residual, which is called vermicompost or vermi cast. Worms that have been used in the treatment of faecal sludge (*Eisenia Fetida* and *Eudrilus Eugeniae*) are robust to feedstock variations. Worms can consume 1.5-2 times more wastewater sludge than their bodymass per day (Eastman *et al.,* 2001), and a cast production rate of 0.25-0.32 g cast/g worm.day was reported when feeding on human faeces (Yadav *et al.*, 2012). Pathogen inactivation can occur as the feed passes through the worms, in contrast to compost where the pathogen inactivation mechanism is heat; however, this still needs to be confirmed and tested for faecal sludge.

Three studies in Mexico, the Philippines and India assessed vermicomposting of faeces, and faecal sludge collected from septic tanks (Rodríguez-Canché *et al.,* 2010). These studies confirmed that worms require bedding material such as paper and cardboard for proper development. The studies also confirmed that high ammonia concentrations can be toxic to worms and hamper their development. The worms were not able to survive on untreated sludge as a feed source, and required stabilized faecal sludge.

Black soldier fly

Treatment of faecal sludge with BSF larvae produces larval biomass that is high in protein and can be used as animal feed (e.g. for poultry and fish). As BSF larvae feed on faecal sludge, they gain body mass. The ratio of feedstock provided to the larvae and the corresponding larval biomass yield is called the bioconversion rate. Based on research in Sweden and Kenya, the bioconversion rate of BSF treatment of faecal sludge is between 10-20% of the sludge dry weight (Banks, 2014; Sanergy and Lalander, personal communication). For BSF treatment to be economically viable, it normally needs to be in the order of several tons of faecal sludge based on dry weight per day (Gold *et al.,* 2018).

Under optimal process conditions (e.g. temperature and nutrients), black soldier larvae typically develop in 14-16 days into full-grown larvae. Following the larval stage, they become flies. BSF do not feed during their adult lives, resulting in the reduced risk of disease transmission (i.e. vectors). Based on bench-scale and pilot-scale testing in Sweden, Thailand and Kenya, with faeces and faecal sludge from septic tanks, fly larvae can reduce the mass of sludge by between 40-60% based on dry weight (Lalander *et al.,* 2013b; Diener *et al.,* 2011). Recommendations are not yet available for feeding rates with faecal sludge. However, recommendations for other biowaste are 100-125 mg wet feed per larvae and day with chicken feed (60% moisture content) (Diener *et al.,* 2009). Larvae can be fed once, or periodically, for example every fourth day at a larvae density of 40,000 larvae per m^2 container surface area (Dortmans *et al.,* 2017). A study with faeces used a feeding rate of 80 g faeces and a feeding frequency of every 3-4 days (Lalander *et al.,* 2013a).

Figure 5.4.1 Close-up of black soldier fly larvae (source: Dortman *et al.*, 2017, ©Sandec-Eawag).

For information on how to set up a complete BSF processing facility with biowaste, refer to *Black Soldier Fly Biowaste Processing – A Step-by-Step Guide* by Dortmans *et al.* (2017). As guidelines are not yet available for faecal sludge, any setup would have to include an experimental phase to determine bioconversion rates, feeding frequency, organism density, faecal sludge mass reduction, and optimal temperature, humidity and lighting, with continued ongoing monitoring during operation.

Adaption to faecal sludge for vermi and fly larvae treatment

A theoretical way of identifying the suitability of faecal sludge feed for vermi and fly larvae treatment is to determine nutrient parameters (e.g. protein, carbohydrates, fiber and lipids). However, a more practical approach is to conduct a feeding trial with different feed compositions. The feeding trial must be operated as the anticipated treatment system. It is important to gradually introduce faecal sludge as a feed, typically starting to feed with 10% faecal sludge and 90% biowaste, and moving towards 100% faecal sludge over time. It could take weeks for the worms to acclimatize to a new food source, while the BSF larva either thrive or are not compatible with the feed. Depending on the faecal sludge qualities, the adjustments, feeding frequency, quantities and mixing ratios with other feed will be different. Prior to feeding, the faecal sludge needs to be dewatered to approximately 60-90%; typically warmer climates allow feed with higher moisture contents than colder due to evaporation (Dortmans *et al.*, 2017). See Table 5.4.1 for a summary of the relevant design parameters.

Table 5.4.1 A summary of relevant design parameters when designing for vermi and fly larvae treatment.

Parameter	Unit	Design relevance
Ambient temperature	[°C]	Optimal operating temperatures are critical for operation, larvae will not digest the feed and grow. For BSF 25-32°C (Dortmans *et al.*, 2017).
Feed	[-]	The organisms have to be compatible with the feed to grow. Typically requires co-feeding with other biowastes and a feed ratio need to be determined.
Feeding rate	[g wet FS/day.organism]	The maximum incoming faecal sludge that can be treated.
Organism density	[organisms/m^2]	The number of organisms that are required to treat the incoming faecal sludge. Worms and larvae need to be purchased or procreated.
Moisture content of the feed	[%]	Faecal sludge needs to be dewatered to 60-90% prior to feeding the organisms.

Example 5.4.1 Theoretical example

The following example illustrates the theoretical amount of endproduct that a faecal sludge treatment plant receiving 10 m^3 faecal sludge with a TS of 4% per day can produce. Assuming a faecal sludge density of 1 kg/L, 10 m^3 faecal sludge results in 400 kg total solids.

$$10\ \text{m}^3\text{FS} \times 40\,\frac{\text{kg TS}}{\text{m}^3\ \text{FS}} = 400\ \text{kg total solids (TS)}$$

Further assuming a bioconversion rate of 10-20% results in the larvae accumulating 40-80 kg dry body mass that can be sold as feed.

$$400\ \text{kg} \times 0.1 = 40\ \text{kg dry bodymass}$$

$$400\text{kg} \times 0.2 = 80\ \text{kg dry bodymass}$$

However, remember that the larvae convert organic solids to biomass, and in a faecal sludge treatment plant there is a high risk that the TS content also includes a large share of sand and gravel. Therefore, there is a need for a large amount of incoming faecal sludge to produce an adequate volume of dried larvae for financial viability.

Case study 5.4.1 Why black soldier flies are still an innovative faecal sludge treatment technology

Doctoral studies by Moritz Gold, Eawag and ETH Zurich

Reliable and economic operation of a BSF larvae facilities typically relies on a variety of different biowastes as feedstock. These biowastes can be a combination of faecal sludge, fruit and vegetable wastes (e.g. from markets), house and restaurant waste, brewery and milling wastes. Currently, operating with this variety of biowastes is a challenge, as nutrients and microbes that differ between these biowastes result in variable process performance (e.g. time that larvae need to develop, amount of larvae produced from one unit of biowaste).

A doctoral thesis at Eawag and ETH Zurich is focussing on understanding the influence of different nutrients and microbes on BSF process performance. Similar to composting, which uses the carbon and nitrogen ratio to identify a suitable process window, the research is working towards identifying metrics for BSF processing. This metric is probably different to the one developed for other treatment technologies based on microbes which can use several forms of carbon and nitrogen for their metabolism, because BSF larvae development relies on proteins, amino acids and available carbohydrates (Gold *et al.,* 2018).

The anticipated output is a guideline that treatment operators can use in the future to identify formulations of different types of biowaste for reliable treatment process performance. This would contribute to meeting treatment objectives and producing marketable treatment endproducts from faecal sludge.

Exercises

1. What are the treatment objectives when treating faecal sludge with:
   a) Vermicomposting
   b) BSF treatment
2. One common reason for using vermicompost and/or BSF treatment is the resource recovery and revenue potential from the treatment endproduct. Name endproducts of treatment from:
   a) Vermicomposting
   b) BSF treatment
3. You are a treatment plant operator that want to sell the BSF larvae as animal fodder to farmers. What parameters will tell you how many kilos of dried larvae can be expected from the incoming faecal sludge?
4. Prior to the design of either vermi or fly larvae treatment, it is important to conduct trials to determine and optimize operating conditions. List the operational parameters that should be monitored and evaluated, and briefly explain why.

5. Name and explain two differences between vermi and fly larvae treatment.
6. Protection of public health is the most important treatment objective for faecal sludge treatment.
   a) Describe what protective measures can be taken for employees during the treatment process and for protection of public health in vermi and fly larvae treatment.
   b) Describe further treatment requirements of vermicompost and BSF prior to enduse.
7. Worms and larvae are living organisms and will only feed, grow and reproduce in suitable environmental conditions. Name five environmental parameters that are important for the growth of these organisms.
8. How can treatment systems based on vermi and fly larvae treatment deal with the large fluctuations of incoming quantities and qualities of faecal sludge?
9. The recommended moisture content of feed for vermi and fly larvae feed is 60-90%. How can the moisture content of the feed adapt in
   a) Dry climates
   b) Moist climates
10. High levels of ammonia in faecal sludge could potentially upset worms and larvae. Why?
11. In your opinion, what should be considered when creating laws and regulations regarding the sale of treatment products from vermicompost or black solider fly larva? Discuss in 200 words.
12. You are operating a faecal sludge treatment plant that receives faecal sludge from public toilets that have short retention times and high total solids content. Next month, you will also start receiving faecal sludge from household septic tanks that are emptied on average every ten years. What preparations should you take prior to the changeover in feed, to maintain adequate treatment and ensure the process is not disturbed?
    a) For vermicompost
    b) For BSF larva
13. How many BSF larvae are required to treat 100 m^3 faecal sludge per day that has been dewatered to a TS concentration of 60 kg per m^3 faecal sludge? Assume feeding of the larvae every fourth day, a larvae density of 40,000 larvae/m^2 container, and a feeding rate of 100 mg wet FS per larva and day.
14. You are operating a faecal sludge treatment plant, and decide to use BSF to reduce solids for disposal, and to generate revenue from resource recovery. Assume the mass reduction of the initial faecal sludge to be 50% by dry weight, and that the treatment unit will receive faecal sludge six days a week. How much faecal sludge is remaining after three weeks with a daily loading of 10 m^3 faecal sludge dewatered to a moisture content of 70%?

Technology

Chapter 5.5

Lime stabilization and ammonia treatment

Miriam Englund and Linda Strande

Learning objectives

- Explain pathogen inactivation through ammonia and lime treatment
- Discuss the operation and maintenance requirements
- Discuss the considerations for implementation

Textbook

Available at www.sandec.ch/fsm_book

- Strande, L., Ronteltap, M. and Brdjanovic, D. (2014). *Faecal Sludge Management - Systems Approach for Implementation and Operation*.

Free online course (MOOC)

Available at www.eawag.ch/mooc

- *Introduction to Faecal Sludge Management.* MOOC series by Eawag and EPFL. Module ´Innovations in ammonia and lime treatment´.

Guidelines for faecal sludge

- USAID (2015). Implementer's Guide to Lime Stabilization for Septage Management in the Philippines.

Additional resources

- Anderson, C., Malambo, D.H., Perez, M.E.G., Nobela, H.N., de Pooter, L., Spit, J., Hooijmans, C.M., Van De Vossenberg, J., Greya, W., Thole, B., van Lier J.B., and Brdjanovic, D. (2015). *Lactic acid fermentation, urea and lime addition: promising faecal sludge sanitizing methods for emergency sanitation.* International journal of environmental research and public health, 12(11), 13871-13885.
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- Greya, W., Thole, B., Anderson, C., Kamwani, F., Spit, J. and Mamani, G. (2016). *Off-Site Lime Stabilisation as an Option to Treat Pit Latrine Faecal sludge for Emergency and Existing On-Site Sanitation Systems.* Journal of Waste Management, 2016.

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Introduction

The main treatment objective for both lime stabilization and ammonia treatment is pathogen inactivation through chemical addition. Lime stabilization is in the transfer phase of development, whereas ammonia treatment is still in the innovative (research and development) phase and needs further research prior to developing recommendations. Lime stabilization has been implemented in the Philippines (USAID, 2015), and for emergency faecal sludge treatment in Cox's Bazar, Bangladesh, due to its simple operation and because hydrated lime, also known as calcium hydroxide ($Ca(OH)_2$), is usually readily available to be bought.

Lime stabilization

Lime stabilization inactivates pathogens by raising the pH of faecal sludge to >11 for a minimum of 2 hours. Such a high pH also has the benefit of slowing down or stopping biological processes that are responsible for odours, and can improve solid-liquid separation. Mixing to ensure an even distribution is crucial for the success of lime stabilization, which can require considerable effort with dense faecal sludge. It is important to consider that this process is only temporary and pathogen regrowth is likely when the pH drops below 11, for example during storage, transport or use of the treatment product.

Resource recovery options are affected by the addition of lime or urea. In the case of lime stabilization, the calorific value for solid fuel usage decreases, microorganisms that are important for co-composting are inhibited, and the high pH as a result of lime stabilization is not beneficial for non-acidic soils if used for land application.

Ammonia treatment

Ammonia treatment relies on high concentrations of ammonia within the cell membrane, which is toxic to bacteria, and can hence reduce pathogens. The amount of either ammonium (NH_4^+) or ammonia (NH_3) that is present in a solution is pH-dependent, based on its chemical equilibrium (Figure 5.5.1). Therefore increasing the pH is an important component of ammonia treatment. Ammonia can be added in the form of urea (CH_4N_2O), either as a chemical nitrogen-fertilizer or with urine. When urea is added to faecal sludge or separately collected faeces, the pH slowly increases over time because of the transformation of urea to ammonium and ammonia. The pH can also be increased by adding for example hydrated lime. However, it should be noted that the urease enzyme can be inactivated above pH 10.

This is one reason why the correct dosing schemes for this technology are still subject to research.

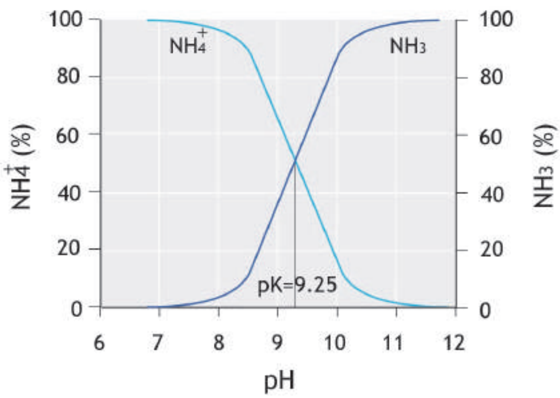


Figure 5.5.1 Ammonium and ammonia distribution as a function of pH (Kunz *et al.*, 2016).

Only a few experiments have been carried out with ammonia treatment on a laboratory scale. Ammonia treatment requires a jar test to find the optimal chemical dosage (and of the pH-raising agent if required). It also requires a test to evaluate the intrinsic ammonia content of the faecal sludge. A laboratory study in Blantyre, Malawi, showed that a dosage of 2–2.5 % urea on a wet basis was needed to sufficiently treat faecal sludge (Anderson *et al.,* 2015). Another study concluded that a dosage of 3 % urea on a wet basis was needed (Vinnerås, 2007). The time period for treatment is based on the initial ammonia nitrogen content. Some experiments show that with a pH of approximately 9–9.4, ammonia treatment has been observed to take from 1 h up to 7 days based on detectable total coliform limits (*Anderson et al.,* 2015; Vinnerås, 2007). Ammonia treatment needs to be handled in sealed containers since ammonia is a gas, which can volatilize and be lost to the environment.

Sizing of lime stabilization

The approach to lime stabilization can be summarized in a step-by-step approach, see Table 5.5.1. In the future when more information becomes available for ammonia treatment the same approach could be used.

Table 5.5.1 Step-by-step approach for lime stabilization.

Step 1	Establish design criteria
Step 2	Determine chemical dosage
Step 3	Optimize and monitor mixing conditions
Step 4	Determine treatment plant requirements

Step 1: Establish design criteria

To be successful, lime stabilization relies on a suitable dosage of a chemical and on proper mixing. The required dosages are found as a function of the total solids (TS) content and/or by a bench-scale jar test.

- Q_s : Daily inflow of faecal sludge [m^3/d]
- C_{TS_in}: TS concentration of influent faecal sludge [kg TS/m^3]

Step 2: Determine chemical dosage

First, quantify the TS concentration of the incoming faecal sludge. The average dosage of lime in a number of lime stabilization applications in the United States (with septic tank sludge) and the Philippines was 19–50 % lime per kg TS in septage to raise the pH to 12 (USAID, 2015). However, in one study in Blantyre, Malawi, the addition of 10–35 % lime per kg TS was successful in increasing the pH to >11 (Greya *et al.,* 2015). This variation in the results is due to the variability of faecal sludge characteristics, which influence the treatment performance. Therefore, it is always recommended to conduct bench-scale jar tests to find the optimal lime dosage.

Step 3: Optimize and monitor mixing conditions

Mixing occurs in two steps, first, a lime slurry mixture needs to be made by combining 1 kg hydrated lime with 3 L water (USAID, 2015). If there are clumps of undissolved hydrated lime in the bottom of the bucket, add more water and stir again. Next, add the lime slurry to the faecal sludge directly after mixing to avoid settling. Pre-mixing the lime into a slurry facilitates the mixing with faecal sludge, increases the pH in the faecal sludge and also reduces dust which can cause skin and eye irritation.

Mixing the lime slurry and faecal sludge together can be done mechanically or manually, but needs to be done thoroughly to ensure adequate treatment and that the pH is consistent throughout. Make sure that the lime slurry and faecal sludge are mixed for at least 5 min in the container before measuring the pH. The pH should be >11 for at least 2 hours. If the pH is not high enough, add more lime slurry (1:3 lime to water ratio), and stir again until a pH of >11 is reached. Throughout the 2 hours, continuous mixing and pH measuring is beneficial. If done manually, an interval of mixing and measuring every 30 min is the minimum requirement. (USAID, 2015)

It is important to note that once the pH >11 is reached and the 2-hour mixing period has begun, more faecal sludge should not be added to the mixture.

Step 4: Determine treatment plant requirements

The treatment plant operators need to be taught how to work with chemicals properly and how to handle medical emergencies. Safety precautions need to be in place, as the hydrated lime can cause severe skin irritation and permanent damage (e.g. blindness). Personal protective equipment, including eye goggles, long-sleeved shirts, filter masks and boots are mandatory. In the absence of protective equipment, eye irritations and skin rashes are common complaints. First aid kits and possibilities for rinsing of the eyes with hygienic safe water need to be provided. In addition, there needs to be access to water and cleaning stations for equipment and personnel.

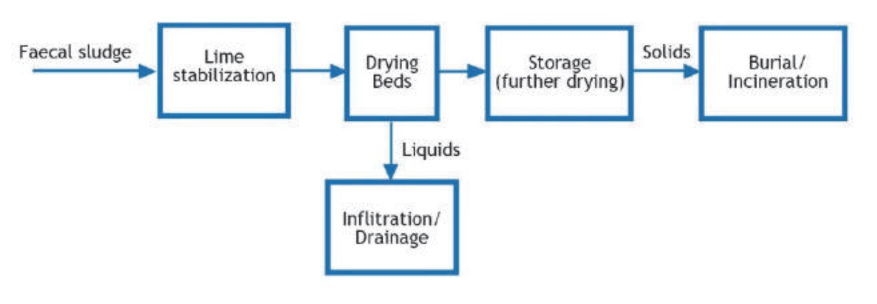
Hydrated lime usually comes as a powder, which requires dry and cool storage to avoid solidification. The container used for mixing lime slurry and the faecal sludge must be lined, with a material resistant to lime, and be large enough for the treatment retention times.

Case study 5.5.1 Lime stabilization in emergencies

Case study based on the work of the International Federation of Red Cross and Red Crescent Societies (IFRC).

In February 2018, the IFRC designed and implemented lime stabilization in the Kutupalong-Balukhali refugee camp in Cox's Bazar, Bangladesh. Latrines were emptied by a team of four people with buckets, or electrical pumps, into barrels. The team then carried the barrels to the treatment plant with bamboo sticks and ropes.
The process flow included:

- Lime stabilization for pathogen inactivation
- Drying beds for solid-liquid separation
- Soil infiltration for disposal of leachate
- Storage for further drying and pathogen inactivation of the solids through starvation, predation and age, and
- Burial or incineration for safe disposal of solids.



The treatment objective was identified as pathogen inactivation to protect public health. Lime stabilization was carried out in ~100 L batches in 120 L barrels. Field-based jar tests, where the pH was measured over time, were conducted to assure reasonable dosing to reach a pH >11 for a minimum of 2 hours. However, due to the emergency context, optimization of the lime dosage was not prioritized and hence, a dosage of 15 g lime/L faecal sludge was used. Resources were not available to measure TS, so assumptions were made based on the faecal sludge volume. The lime was mixed with water and added to the barrel as a pre-mixed lime slurry (1 kg hydrated lime to 1 L water). It is important to note, that the water to lime ratio could potentially be affected by the quality of the hydrated lime.

Figure 5.5.2 **Operator pouring the lime slurry into a barrel filled with faecal sludge in Cox's Bazar, Bangladesh.**

The operators stirred the mixture of faecal sludge and lime slurry with a bamboo stick for 5 minutes followed by pH measurements and repeated stirring once an hour. It was assumed that complete inactivation of pathogenic bacteria and viruses occurred after the pH of the faecal sludge was raised to pH >11 for a minimum of 2 hours.

The main challenges included;

- Acquiring lime powder with a sufficiently high concentration of hydrated lime was difficult to source locally; the in-field team noticed the lime was poor quality because of the difficulty in raising the pH >11. The quality of hydrated lime purchased from local paint shops turned out to be too low, and in the end, the powder had to be bought from a distributor of laboratory chemicals.
- The pH meters were repeatedly damaged by the lime dust, and needed to be replaced frequently. In the absence of a full laboratory, the pH value was the only way of evaluating the treatment success, and therefore the pH measuring devices needed to be functional.

Lime stabilization has the benefit of being a proven treatment option, and readily easily implemented in emergency settings. However, lime stabilization requires an available supply chain for hydrated lime, as well as adequate monitoring, and it limits resource recovery options. The IFRC has recently introduced a faecal sludge field lab for process control of the lime stabilization, and the field laboratory methods are currently being validated to suit the context.

Exercises

1. What is the reason for pathogen inactivation in
   a) Lime stabilization
   b) Ammonia treatment
2. Stirring of the mixture of lime slurry and faecal sludge is a requirement to ensure the treatment performance. Why?
3. Lime is dosed on the basis of the TS content of faecal sludge. One potential challenge with this method is the variability of TS content in the faecal sludge. Discuss how this challenge could be addressed if it is not possible to measure TS.
4. After 2 hours of lime stabilization at pH >11, the faecal sludge solids will be disposed of by either incineration or burial. Discuss the benefits and drawbacks of both options.
5. You are working in a warehouse selling hydrated lime to organizations operating lime stabilization in a refugee camp. One of the organisations calls you and says that something is wrong with the hydrated lime since the whole bag is hard as a stone; what do you answer?
6. An appropriate chemical quality is a key consideration for successful treatment in lime stabilization and ammonia treatment. Typically when purchasing lime at a local market, there will be a trade-off between price and quality. What determines the quality of lime used for faecal sludge treatment?
7. Studies show that diluting the hydrated lime with water, prior to adding it to the faecal sludge, facilitates the pH increase and reduces the amount of hydrated lime required. Discuss the reasons for this.
8. Personal protective clothing and water access are important factors when conducting lime stabilization and ammonia treatment. List common personal protection equipment and describe in one sentence why they are needed.
9. Ammonia treatment is not always sufficient with high water contents for successful treatment. What is the reason?
10. Two engineers are discussing potential vessels for ammonia treatment. One suggests a square open basin, to facilitate mixing and monitoring of the process. The other one suggests a sealed container. Which engineer is right and why?
11. Ammonia treatment results in more beneficial treatment products compared to lime stabilization. Explain why, and give two examples of potential treatment products from ammonia treatment.
12. You are asked to design a time and space-efficient faecal sludge treatment option for a slum area on the outskirts of a densely populated city with 20,000 inhabitants. The space is very limited and the weather very unstable; fluctuations of ±10 °C are common. Disposal in a few small-scale brick factories is the only end-use alternative. Ammonia treatment and lime stabilization are suggested. Which of the two treatment options would you recommend? Give at least three reasons why.

13. You are conducting a jar test to find out if a dosage of 20 %, 25 % or 30 % of hydrated lime per kg TS is most suitable. Each jar is filled with 1,000 mL faecal sludge with a TS content of 6 g/L faecal sludge.
    a) How much hydrated lime powder with a content of 80 % $Ca(OH)_2$ is required for each dosage?
    b) How do you know which test is best?

14. How much hydrated lime is required if you have 5 m^3/day incoming faecal sludge with a TS content of 10 g/L faecal sludge? Jar tests showed that dosing of 20 % $Ca(OH)_2$ per dry mass of faecal sludge would be sufficient, and the lime powder on the market contains 86 % $Ca(OH)_2$.

15. You are asked to calculate the required volume (in m^3) of a reactor tank for one day of incoming faecal sludge. Also, discuss the challenges resulting from the required volume. Calculate the amount of hydrated lime and water required to treat 8 m^3 faecal sludge/day. Use the information summarized in the table below:

Parameter	
Incoming faecal sludge	8 m^3 faecal sludge per day
Lime slurry ratio	1 kg lime to 3 L water
Lime dosage	0.2 kg lime to 1 kg faecal sludge
TS of incoming faecal sludge	4 g TS/L faecal sludge

Globally, a third of the world's population is served by onsite sanitation. The reality is that onsite sanitation is here to stay, either as an intermediate or permanent standalone solution, or in combination with sewer-based systems. The appropriate and adequate management of faecal sludge deriving from onsite technologies is imperative for the protection of human and environmental health. The book 'Faecal Sludge Management: Systems Approach for Implementation and Operation' was first published in 2014 and is used by practitioners and universities around the world. Since its publication, the sector has been rapidly growing and adapting to address the need for faecal sludge management. To keep pace with rapid developments, publications are needed that can adapt more quickly than the time required for new books and book editions to be published. Therefore 'Faecal Sludge Management: Highlights and Exercises' has been developed as a more flexible publication that will be regularly updated. It is largely based on information that was put together during the production of our online courses, and is intended to be used as a companion to existing publications, providing highlights of selected topics together with learning examples.

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