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

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OBJECTIVES

The objectives of this chapter are to:

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

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4.1 INTRODUCTION

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

The current state of knowledge in faecal sludge treatment covers technologies that are either *established, transferring,* or *innovative* (Strande, 2017; WHO, 2018). *Established technologies* are those where adequate knowledge exists on how to make recommendations for their full-scale design and operation to protect public and environmental health. Examples of established technologies include settling-thickening tanks, drying beds, co-composting, and stabilisation ponds. Experimentation is important for established technologies in order to optimise their use and performance, to further understand treatment performance and mechanisms, and to monitor in order to ensure treatment performance is adequate. *Transferring technologies* are those that are already established in other applications, such as wastewater treatment, and appear promising for use in FSM. Their use has not yet been widely established in FSM, but ongoing research is helping to establish their use and effectiveness. Examples of transferring technologies include mechanical dewatering, conditioners, alkaline treatment, incineration, anaerobic digestion, pelletising, geotextiles, and thermal drying. Research and experimentation are very important in the transfer of these technologies, because faecal sludge is highly variable and very different in composition from the mixed domestic wastewater for which most biological wastewater treatment plants are designed. *Innovative technologies* are new and emerging technologies that are still under development and not yet established. Due to the level of unknowns, the level of expertise required to design and operate these technologies in a fashion that adequately manages risks is much greater than with established technologies. As further research is carried out, many of them will also become established technologies. Examples of innovative technologies include, but are not limited to, the use of black soldier fly larvae, and ammonia treatment (Chapter 2).

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

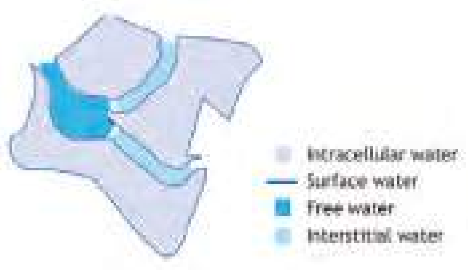

Figure 4.1 Representation of the different forms of water in a sludge floc (adapted from Bassan *et al.,* 2014)

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

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

4.2 EXPERIMENTATION IN FAECAL SLUDGE MANAGEMENT

Before starting experiments, it is important to become familiar with the key elements used in setting up experimental work. Experiments are a way to understand cause-and-effect relationships in a system, by deliberately changing conditions in a controlled fashion, and observing the changes in the system that are produced as a result of what has been altered. An experiment can be defined as '*a series of runs in which purposeful changes are made to the input variables of a process or system so that we may observe and identify the reasons for changes that may be observed in the output response*' (Montgomery, 2019). A run is one component of an experiment, conducted with a specific set of input variables. Tests are measurements of specific faecal sludge characteristics or properties, as described in chapters 2 and 8. Tests can be part of an experiment (*e.g.* measuring pathogen levels in treated faecal sludge), but can also be conducted outside of a planned experiment. For example, laboratory tests are used for routine characterisation to monitor the performance of existing treatment systems.

4.2.1 Scales of experiments

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

Laboratory-scale experiments

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

Pilot-scale experiments

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

Full-scale experiments

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

Working with faecal sludge and with transferring or innovative treatment technologies inherently includes uncertainties and risks that need to be managed. The transitions between laboratory-, pilot-, and full-scale experiments may be iterative and will require time and dedication to achieve high-quality experimental design and execution. It is critically important to incorporate a research component into any faecal sludge treatment project from its inception. Risks can be mitigated by forming partnerships between municipalities and universities/research institutes, which can help guide experimentation from the start of the project to the optimisation and monitoring of a full-scale FSTP (Strande, 2017).

4.2.2 Designing an experiment

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

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

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

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

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

4.3 TRANSFERRING TECHNOLOGY: CONDITIONING TO IMPROVE DEWATERING

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

4.3.1 Introduction to faecal sludge dewatering with conditioners

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

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

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

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

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

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

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

Recent research on the optimal dosing of conditioners for faecal sludge has been based on laboratory testing, which is too time- and labour-intensive to be scaled up. However, it indicates that when the right conditioner and dose are applied, significant improvements to faecal sludge dewatering performance are possible; for example, faster dewatering on drying beds, and cleaner effluent from drying beds, settling-thickening tanks, and geotextiles (Gold *et al.*, 2016). Research needs to be directed at developing methods to rapidly characterise influent faecal sludge quantities and qualities (Q&Q, see Chapter 5) to determine the conditioner dose (Gold *et al.*, 2018, Ward *et al.*, 2019). In addition, considerations such as cost, availability, supply chain, chemical safety, and possible requirement of additional infrastructure (storage tank, dosing device, mixing tank) need to be taken into account when designing experiments and selecting conditioners and dosing processes to apply at pilot- and full-scale.

4.3.2 Types and mechanisms of conditioners

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

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

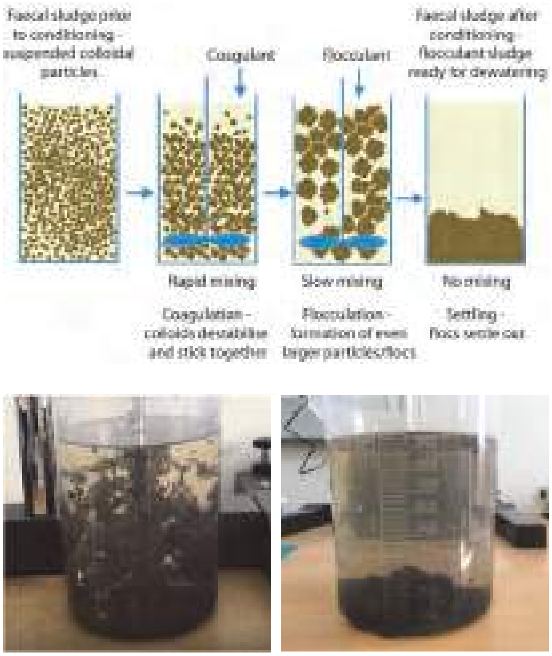

Figure 4.4 Above: steps in faecal sludge conditioning, coagulation, flocculation, and sedimentation; below left: flocculation of faecal sludge; below right: settling of faecal sludge flocs (figure: adapted from Ward and Strande, 2019, photos: IHE Delft).

4.3.3 Key parameters for selection of conditioners and optimal dose

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

- *Faecal sludge properties*: conditioners are commonly dosed as a function of total suspended solids, or with faecal sludge often total solids is used in the absence of total suspended solids measurements. Other factors such as the electrical conductivity or the degree of stabilisation may influence which type of conditioners work best.
- *Dewatering technology*: conditioners need to be compatible with technologies used for dewatering. For example, centrifuge dewatering requires conditioning with polymers that produce flocs that are resistant to high shear (*i.e.* very high molecular weight, and usually branched or structured polymers).
- *Mixing conditions*: complete mixing of faecal sludge with conditioners is necessary to make the particles collide and stick together (coagulate) and grow into flocs (flocculate); however, mixing speeds need to be selected to avoid floc destruction. Mixing for coagulation needs to be vigorous in order to cause many particle collisions. However, mixing for flocculation needs to be gentle to keep flocs from breaking up. This should also be considered during the selection of pumps for example, for the transfer of conditioned faecal sludge from a settling-thickening tank to a drying bed.

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

4.3.4 Laboratory- and pilot-scale testing

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

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

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

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

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

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

4.3.5 Case studies – conditioning for improved dewatering

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

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

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

Research question

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

Response variables

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

Factors, levels, and ranges

- Type of conditioner tested.

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

Factors that might influence the response variables

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

Experimental design details

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

Interpreting the results

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

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

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

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

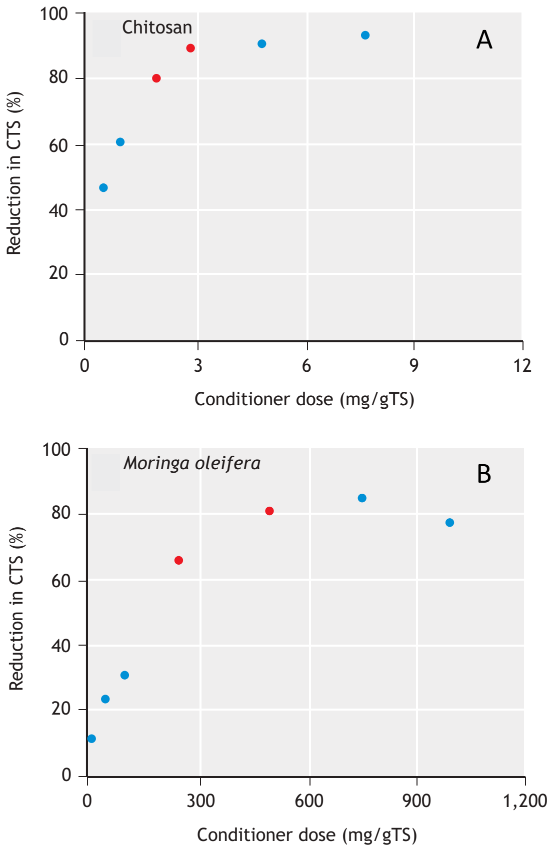

Figure 4.8 A) Results of jar tests with chitosan. B) Results of jar tests with *M. oleifera*. The red dots indicate the optimal dose of each conditioner.

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

Scaling-up from laboratory to pilot-scale

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

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

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

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

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

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

This case study is based on research by Naomi Korir, Jonathan Wilcox, and Catherine Berner at Sanivation in Naivasha, Kenya. This pilot-scale research was done to inform the design of a full-scale dewatering process for a new FSTP in Naivasha, Kenya (capacity 4,000 tonnes faecal sludge per month, delivered by vacuum trucks from pit latrines and septic tanks). Requirements for the plant included a small treatment footprint for the dewatering step, and economic viability. Previous laboratory-scale research characterised hundreds of samples of faecal sludge from Naivasha and established the selection of polymer conditioner and the optimal dose for flocculation. Sanivation wanted to scale up dewatering with geotextiles. To do this requires experimentation for the online dosing, as presented in Section 4.3.1. Because of the iterative experimental approach, questions should be answered one at a time. Therefore the following experiments were carried out on the assumption that geotextiles would work. The pilot-scale setup was sized to process sludge from one vacuum truck at a time, and was designed to test different online conditioner dosing and mixing configurations followed by a subsequent dewatering step using geotextile skips suspended on metal supports (Figure 4.10).

Research question

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

Response variables

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

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

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

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

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

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

Factors, levels, and ranges

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

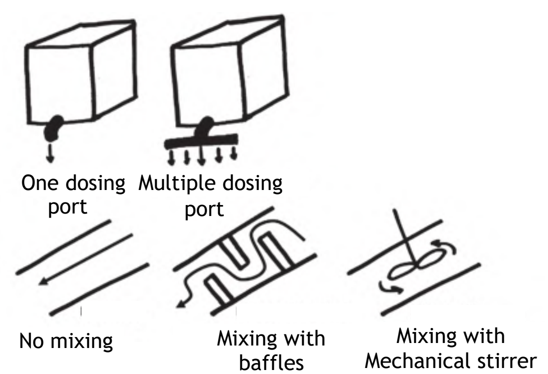


Figure 4.11 Diagram representation of the different conditioner dosing and mixing configurations evaluated by Sanivation.

- Conditioner doses: the laboratory-scale conditioner experiments indicated that the optimal polymer conditioner dose was 2 g polymer per kg faecal sludge; however, the Sanivation team suspected that due to different mixing conditions at the pilot-scale, the optimal dose for the scaled up process could be different. Doses of 2-60 g polymer per kg faecal sludge were tested at the pilot-scale.
- Geotextile cleaning methods: geotextiles were cleaned to determine whether their lifetime could be extending by cleaning between receiving batches of faecal sludge. Three cleaning methods were investigated detergent, detergent + salt, detergent + salt + high-pressure water rinse (Figure 4.12).

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

Factors that might influence the response variables

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

Experimental design details

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

Interpreting the results

The optimal conditioner dose was not directly transferable from lab-scale studies to pilot-scale. Different, less ideal mixing conditions at the pilot-scale called for increased doses of polymer to be used to account for incomplete mixing with sludge particles. Multiple dosing ports performed better than a single port, and the addition of both baffles and mechanical mixing led to the most thorough mixing of conditioner and subsequently the shortest dewatering times in the geotextile skips (less than 5 days compared to 14 days with not optimal conditioner dose) and highest filtration efficiency. With the optimal setup, polymer doses from 2-8 g/kg produced the best results. Overdosing occurred at doses over 8 g/kg, resulting in immediate clogging of the geotextiles and a prolonged dewatering time. The team continued to experience issues with achieving precise dosing with respect to TS. Because of this, it was difficult to avoid overdosing even when doses < 8 g/kg were targeted.

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

Scaling-up from pilot to larger-scale FSTP

Based on their performance at pilot-scale, the Sanivation team decided not to scale up geotextile skips. This decision was based on the estimated land area required for dewatering using performance data from optimised dosing, mixing, and geotextile cleaning processes in place (with mechanical mixing, multiple dose ports, and cleaning between every load cycle). The average residence time in the geotextile skips at optimal conditions was 5 days per truckload. The full-scale FSTP is designed for a capacity of 20-25 truckloads per day, and the footprint of a geotextile skip is 8 m^2. In the best-case scenario involving constant operation 7 days/week and just one day to unload and clean a geotextile skip, 150 geotextile skips would be required, which means 8 $m^2 \cdot 150$ = 1,200 m^2 or 0.12 hectares of land would be required for dewatering (10% of the entire land allotment for the new FSTP). Labour costs were also a significant factor in the decision not to scale up geotextiles. Sanivation also identified that geotextiles can be reused for dewatering up to 10 times with washing in between loadings.

Sanivation is moving forward with the design and implementation of their full-scale FSTP, and will proceed with their optimal polymer dosing configuration. However, the team will switch to a screw press as an alternative, lower-footprint technology. The screw press technology is more resilient to overdosing and the team hopes it will not clog as easily as geotextiles. Screw presses operate continuously instead of being batch processes, allowing for a higher throughput of 20 m^3 sludge per hour. The allotted footprint of the full-scale dewatering process is 120 m^2, an order of magnitude lower than geotextiles would have allowed. Piloting experiments with screw presses are now planned in order to inform the FSTP design. New research questions can be asked, for example, 'What are the optimal operation conditions of the screw press (hydraulic loading rate, conditioner dose, wash water flow rate)?'.

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

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

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

4.4.1 Introduction to resource recovery of faecal sludge as solid fuel

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

4.4.2 Introduction to faecal sludge drying

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

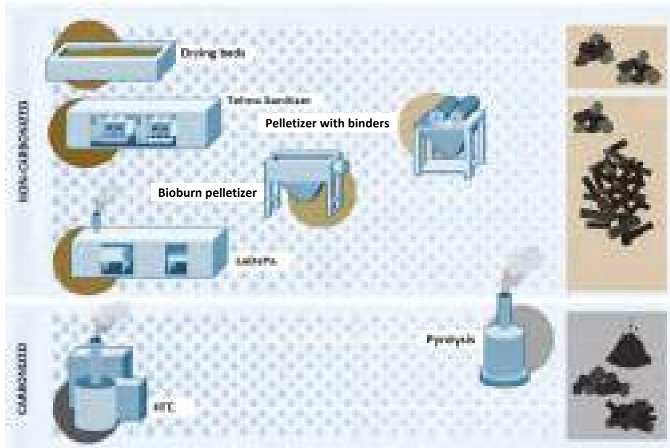


Figure 4.13 An overview of technology options for producing solid fuel, starting from dewatered faecal sludge at 80% moisture and ending at non-carbonised or carbonised solid-fuel end products. The position of the technology icons from left to right indicates the required dryness of the input sludge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

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

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

4.4.3 Types and mechanisms of thermal drying (technical background)

Understanding the underlying physical, chemical, and biological processes supporting a technology is crucial for making informed decisions about adapting it to work with faecal sludge. During thermal drying, heat is transferred to the sludge from a heating source (*e.g.* hot fluid, heated wall, infrared radiation) or generated internally after conversion of another form of energy (*e.g.* microwave, dielectric radiation), leading to the movement of moisture to the sludge surface where it evaporates. The rate of drying depends on the temperature or irradiance from the heat source, humidity, flow rate, and pressure of the ambient air, and on the area, thickness, and thermal properties (*i.e.* heat capacity and thermal conductivity) of the exposed sludge surface. A schematic representation of heat drying of faecal sludge is shown in Figure 4.14.

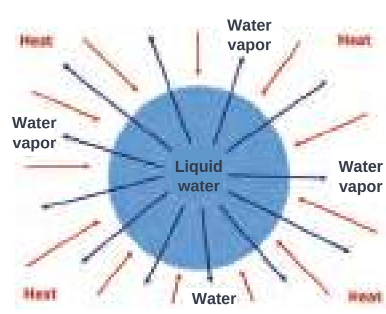


Figure 4.14 Schematic representation of drying faecal sludge. Red arrows represent heat transfer, blue arrows represent mass transfer of water (H_2O).

The most common way to classify thermal drying technologies is according to the heat transfer mode, which are convection (convective drying), conduction (contact drying), and radiation (radiative drying). Convective drying (or direct drying) works by passing hot air or gases directly through the sludge. Contact drying (or indirect drying) instead uses heat exchangers to heat a surface that the sludge is in contact with. Radiative drying provides the heat for moisture evaporation by solar, infrared, microwave, or dielectric radiation. Different types of drying modes can be combined for a given technology. Most drying systems include a ventilation or vacuum system to evacuate the evaporated moisture and avoid saturation of the air, which can inhibit the drying process. In passive drying systems such as drying beds, the sun and wind provide heat and air flow to promote evaporation. For more detailed information about drying mechanisms or types of industrial dryers used in other fields see Mujumdar (2014). Examples of convective, contact, and radiative drying technologies that have been used with faecal sludge at pilot- and laboratory-scales are presented in figures 4.15 to 4.18.

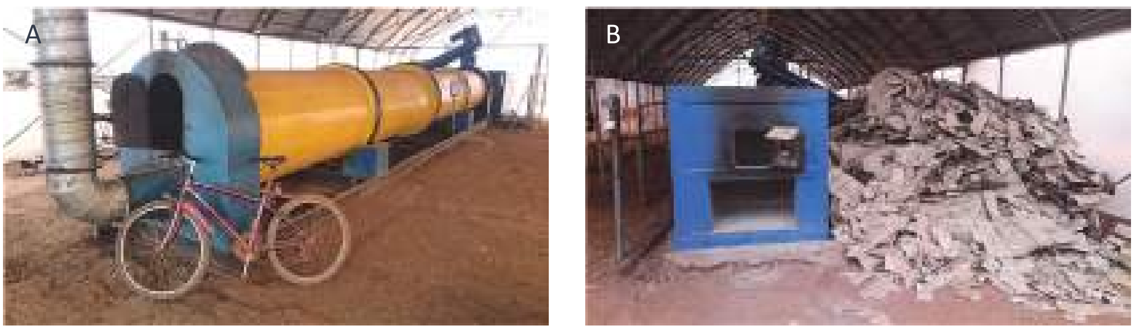


Figure 4.15 A) a rotary convection dryer operated by Pivot, in Kigali, Rwanda and B) waste cardboard is burned in a boiler and the hot gases produced are used as the heat source for drying. The sludge is pre-dried by a solar dryer before entering the convective dryer pictured here (photos: UKZN PRG).

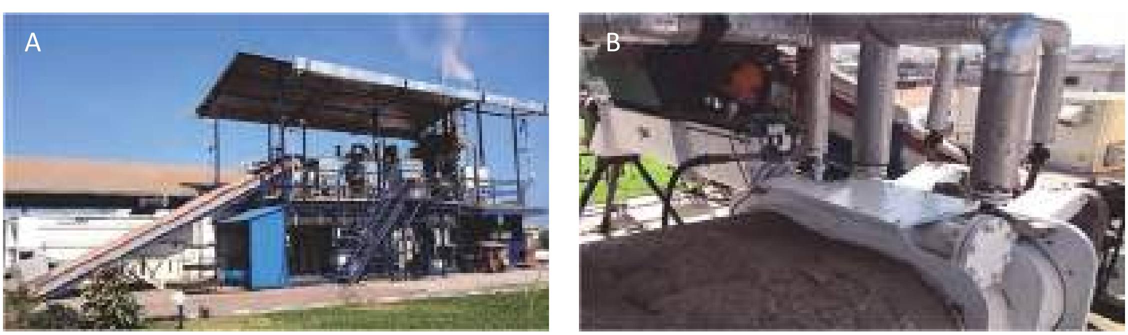


Figure 4.16 A) a contact dryer at the Omni-processor pilot plant at Niayes FSTP in Dakar, Senegal. In this plant, the sludge is incinerated leading to the generation of heat and electricity. B) part of the heat from combustion is recirculated in the process for the drying of the sludge with this contact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

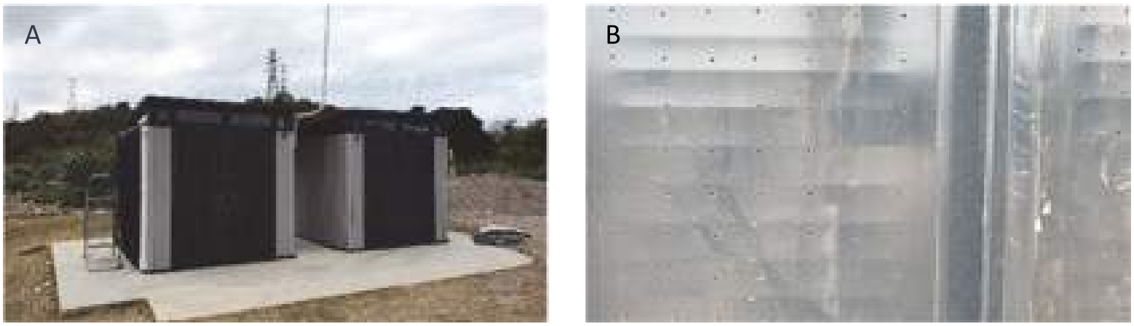


Figure 4.17 A pilot-scale solar dryer developed by Swansea University and tested in Durban, South Africa. A) sludge is placed inside these sheds to dry. B) the walls of the sheds absorb solar energy and transfer it to the sludge inside through a ventilation system (photos: UKZN PRG).

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

4.4.4 Key parameters when implementing thermal-drying technologies

When designing or implementing a drying technology, first the amount of time it takes the sludge to dry to the desired moisture content (*i.e.* the drying rate) needs to be determined, along with the amount of required energy. Optimal combinations of key process parameters will yield dry sludge with the desired moisture content at the lowest energy cost. Methods such as pre-treatment of the sludge with stirring, or techniques to enhance the heat and mass transfer such as mechanical vibrations or ultrasound can also be investigated to improve drying performance. The following factors will influence the drying rate and energy consumption of the faecal sludge drying process, and need to be taken into account during technology transfer and process optimisation (Septien *et al.*, 2018a):

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

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

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

4.4.5 Laboratory-scale and pilot-scale testing

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

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

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

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

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

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

4.4.6 Case studies - thermal drying for energy recovery

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

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

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

Research question

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

Response variable

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

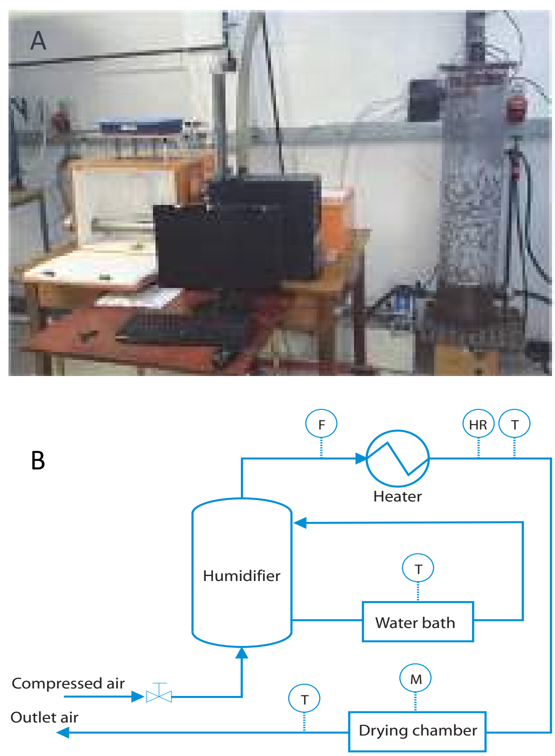


Figure 4.19 A) the custom-designed convective drying rig (photo: UKZN PRG) and B) a schematic representation of the convective drying rig, F: air-flow measurement; T: temperature measurement; M: mass measurement; HR: relative humidity measurement.

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

Factors, levels, and ranges

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

Factors that might influence the response variable

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

Experimental design details

Each run was performed in triplicate. Table 4.2 displays the runs performed in this study from all the possible runs. If all the possible combinations of the selected factors, levels, and ranges had been tested, 108 different runs would have been required. However, this was not feasible in terms of time and resources, therefore the most appropriate combination of runs was selected in order to study the influence of each variable. This was done by varying the value of a single variable while keeping the others constant at a reference value.

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

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

Interpreting the results

The results of the experiment are presented in Figure 4.20.

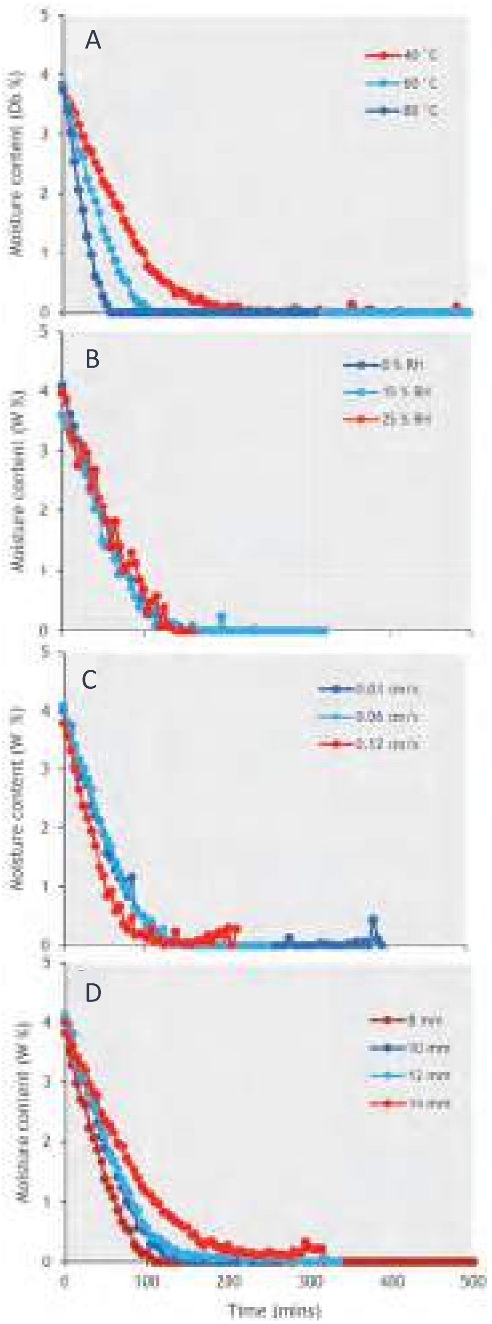


Figure 4.20 A) Drying rate as a function of air temperature, B) relative humidity, C) air velocity, and D) pellet diameter.

The main findings of this study were:

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

Scaling-up from laboratory to pilot-scale

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

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

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

This case study is based on a Master's thesis by Simon Mirara (Mirara, 2017). Further information can be found in Septien *et al.*, 2018a, 2018b, and Septien *et al.*, 2020. The motivation for this research project was to optimise the existing full-scale Latrine Dehydration Pasteurisation (LaDePa) process. The LaDePa process was implemented in the eThewkini municipality in Durban, South Africa to treat the faecal sludge from ventilated improved pit (VIP) latrines through infrared drying, to produce dry, pathogen-free pellets for use as a soil conditioner or solid fuel. The LaDePa process was developed by the eThewkini municipality and Particle Separation Systems as a transferring technology from the mining industry where it was where it was applied for drying of minerals. Based on the treatment performance of the full-scale LaDePa, the municipality decided that it needed to be optimised to minimise energy consumption while maximising the drying rate, pasteurisation performance, and end-use potential in the treated sludge. In order to optimise drying in the LaDePa process and to develop a deeper understanding of the drying process, a 1:10 laboratory-scale replica of the full-scale LaDePa was constructed (Figure 4.2.1).

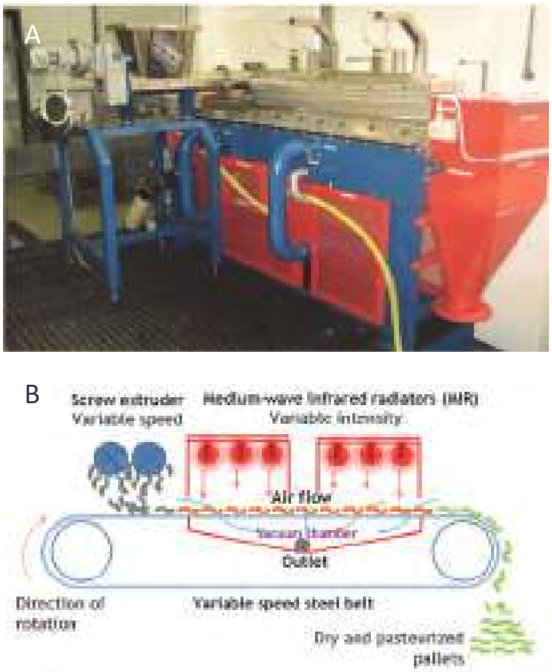


Figure 4.21 A) the laboratory-scale LaDePa, and B) a corresponding schematic representation of the process (photo and schematic: UKZN PRG).

Research question

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

Response variables

The laboratory-scale LaDePa was used to characterise the moisture content of the dried pellets, and energy consumption of the process, at different conditions (see factors, levels and ranges). The sludge was fed into the machine as pellets formed with a screw extruder, which were conveyed by a moving belt under two successive infrared emitters (providing heat for drying). An air stream was induced in the drying zone through an air suction box system installed below the belt to keep humidity low (Figure 4.21).

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

Factors, levels, and ranges

- Emitter intensity (infrared irradiance): 6, 24, and 34 kW/m^2.
- Residence time: 4, 8, 12, 17, 26, and 39 minutes (varied by adjusting the speed of the belt).
- Distance between the belt and infrared emitters: 50, 80 and 115 mm (varied by adjusting the belt height).
- Suction air-flow rate: 11.1 and 18.3 m^3/s.
- Pellet diameter: 8, 10, 12 and 14 mm.

Factors that might influence the response variables

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

Experimental design details

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

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

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

Interpreting the results

Results of the experiment are presented in Figure 4.22.

As expected, the rate of drying increased as the intensity of the infrared radiation increased and the distance between the pellets and the heating source decreased. Drying was faster for pellets with a smaller diameter. Increasing the suction air-flow rate caused a cooling effect on the sludge (negative for the process) but also enhanced the evacuation of moisture from the surface of the pellets (positive for the process). Under the explored conditions, these opposing effects counteracted each other and the overall drying rate was not affected by changing the air-flow rate. The pre-treatment of the sludge also did not affect the drying rate.

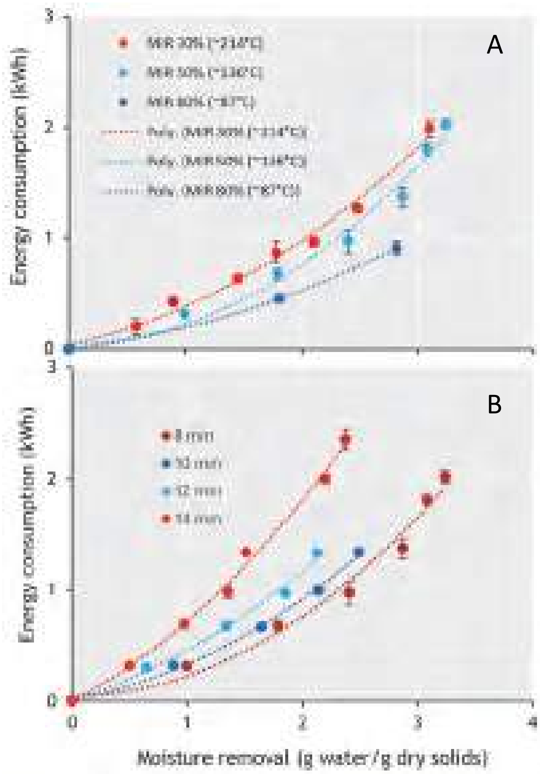


Figure 4.22 A) Plot of moisture removal vs energy consumption at varied medium-wave infrared intensities (MIR). MIR of 30, 50 and 80% equals infrared irradiance of 6, 24, and 34 kW/m^2, respectively, and B) plot of moisture removal vs energy consumption at varied pellet diameters.

The energy consumption for moisture removal was determined from the kinetic data. Depicted in Figure 4.22, the drying process consumes less energy to remove a given amount of moisture when operating at higher infrared heating intensity and with smaller diameter pellets. However, it was observed that drying at too high a heating flux could induce thermal degradation of the sludge, which could lead to charring or burning. During the trials, drying at the highest infrared intensity (34 kW/m^2) resulted in the pellets starting to smoke.

Process optimisation from laboratory- to full-scale

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

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

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

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

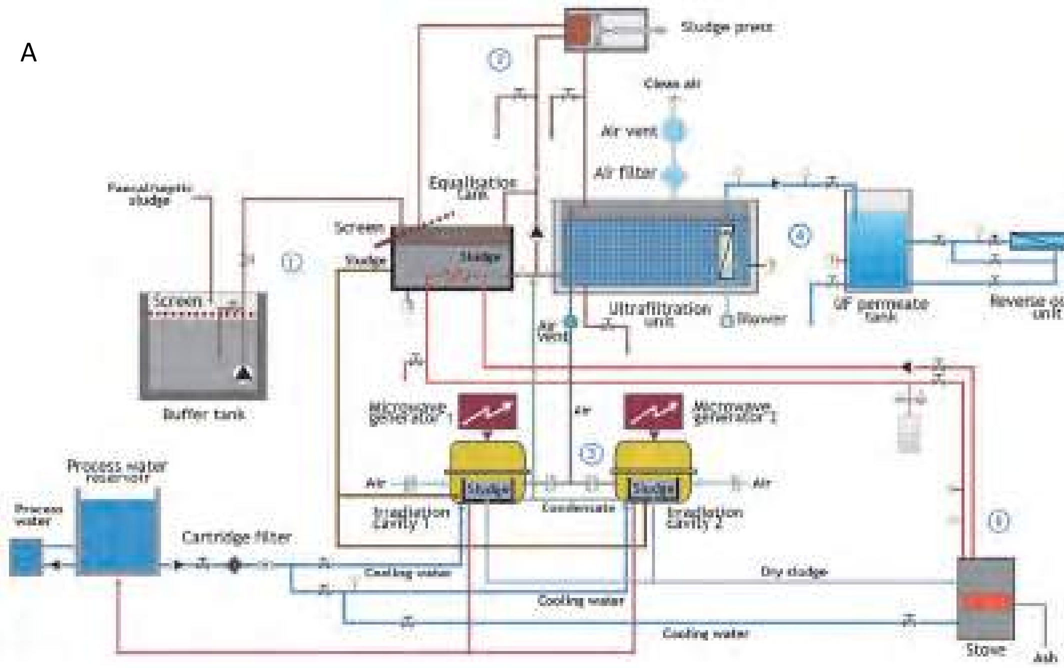
Case study 4.5 *Optimising the Tehno Sanitizer technology for microwave faecal sludge sanitisation and drying*

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

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

All of these shortcomings have been addressed and mitigated in the next generation full-scale prototype: the Tehno Sanitizer. This system is a semi-decentralised and containerised mobile full-scale prototype designed for the treatment (drying, pathogen inactivation, and resource recovery) of diverse types of sludges such as fresh faecal sludge and waste activated sludge, with different water and dry solids contents. This mobile unit has the capacity to process 300 kg of wet sludge per day. The integration of the different technologies provides an attractive approach for treating sludge and wastewater streams generated while producing valuable resources that can be utilised in agricultural and domestic applications, with up to 95% DS. The initial results obtained from studies focusing on pathogen indicator organisms (Mawioo *et al.*, 2016a and 2016b), carried out at laboratory- and bench-scale setups, suggest that the Tehno Sanitizer could be an effective technology for sanitisation of sludge.

A



B

Figure 4.23 A) simplified process flow diagram of the Tehno Sanitizer: (1) sludge intake, (2) sludge pre-treatment, (3) the sludge sterilisation and drying unit, (4) microfiltration, (5) reverse osmosis, and (6) the sludge energy recovery unit, and B) a full-scale Tehno Sanitizer prototype (source: Tehnobiro d.o.o.).

The main challenge addressed in the development of the full-scale prototype was how to minimise the specific energy consumption (SEC) of the system from the value initially observed in the bench-scale unit of 4.0 kWh/L of evaporated water, to the target level of below 1.0 kWh/L of evaporated water.

Research question

Which microwave power output settings on the full-scale prototype achieve the target dryness (85% DS) while minimising the SEC to below 1.0 kWh/L of evaporated water?

Response variables

The experimental setup was designed to measure the SEC (kWh/L) of the system. The SEC was calculated using the power output setting of the microwave generator, set at the desired value (kW). This value was multiplied by the time of the exposure and divided by the mass of water that had evaporated at that exposure time.

The mass of the sludge in the microwave cavity was continuously measured and the moisture content and the DS were calculated from the TS measurement of the sludge sample taken just before the start of the test. Also the sludge temperature was continuously measured by a sensor installed inside the cavity.

Factors, levels, and ranges

Microwave power output: 1.0, 1.5, 3.0, 3.25, 4.5 and 6.0 kW (adjusted manually)

Factors that influence the response variable

The factors that influence the SEC include:

- Energy losses due to the lack of thermal insulation.
- Frequencies at which the microwave energy is delivered.
- Mixing conditions at the irradiation cavity.
- Condensation of the evaporated water in the microwave cavity.
- The microwave energy absorption capacity of the sludge (power density) at the evaluated microwave power outputs.

Experimental design details

Experiments were conducted using the full-scale prototype. The experimental setup (Figure 4.24) consisted of two stainless steel microwave cavities equipped with a rotating polypropylene turntable and an oval sludge-holding vessel, two microwave power supply units, and two microwave generators with a combined power output of 12.0 kW operated at a frequency of 2,450 GHz. An electromotor was used to rotate the sludge samples at a speed of 1 rpm to alleviate the effect of non-uniform sludge heating. Ancillary equipment included an air extraction and treatment unit and a microwave generator-cooling water-based system. In total six identical tests were executed (each at different power level) because only one cavity was equipped with a load cell to continuously measure the mass of the sludge. Each test had a different duration (the shortest was 21 minutes at power output of 6 kW) and lasted until the target DS of 85% was achieved.

Figure 4.24 A) an experimental microwave-based faecal sludge drying unit, and B) samples taken at different points in the process: a) filtrate from the sludge press, b) concentrated sludge from the sludge press, c) ultrafiltration concentrate, d) ultrafiltration permeate, e) reverse osmosis concentrate, f) reverse osmosis permeate, g) dry sludge, and h) condensate (photo: IHE Delft).

Interpreting the results

Figure 4.25 depicts the drying rate as a function of dry solids content at different power outputs of the microwave generators. As expected, the higher the power output, the higher the drying rate. At the start of the drying process the drying rate increased at all the evaluated power outputs until it reached a maximum and constant drying rate value. This constant drying phase was dominant and extended through almost the entire drying process; this is a positive characteristic of the microwave drying process and introduces a competitive advantage compared to thermal drying technologies where such constant drying phases are not commonly observed. Such a constant drying phase is associated with the removal of unbound (free) water from the surface of the sludge which demands much less energy to be evaporated than other types of water contained in the sludge (Figure 4.1).

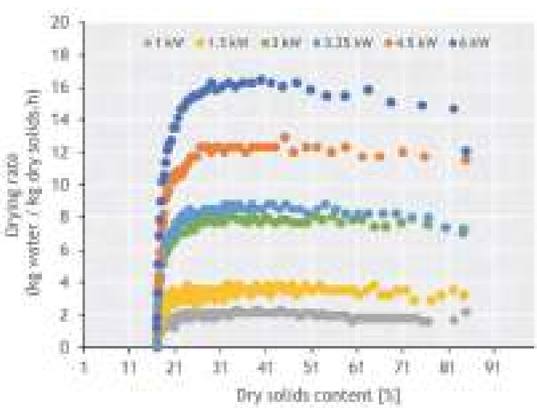


Figure 4.25 The sludge drying rate as a function of sludge dry-solids content at different power outputs of the microwave generators (Kocbek *et al.*, 2020).

Figure 4.26 shows the SEC of the system during the period of drying sludge from 17% to 85% DS at the evaluated microwave generator power output range. It has been observed that increase in power output lowers the SEC. The lowest SEC of approximately 1 kWh/L of evaporated water was reported at power outputs higher than 3 kW. The observed changes in the SEC were due to the microwave radiation generation efficiency which was between 50% (at power below 3 kW) and 70% (at the highest power outputs).

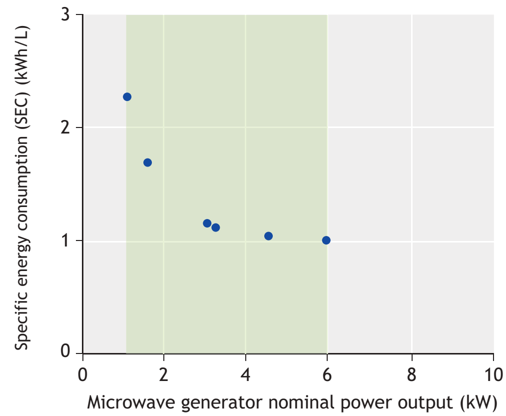


Figure 4.26 Effect of microwave generator power output on the specific energy consumption (SEC) (Kocbek *et al.*, 2020).

Implications of scaling-up

The SEC results obtained in this research provided the evidence that the modifications and innovations built in the Tehno Sanitizer mitigated the early development issues experienced with the Shit Killer, largely reducing the energy requirement resulting in achieving the target SEC of 1 kWh/L. Such results bring Tehno Sanitizer into the mix with conventional thermal drying (convective and conductive) technologies (Bennamoun *et al.*, 2013). Given the fact that in commercial-scale applications a more efficient microwave generator will be used (with an efficiency rate of up to 90%), the SEC is expected to decrease by an additional 10 to 20%. Furthermore, the energy recovery unit in the Techno Sanitizer in this study was not turned on. With the additional heat becoming available from co-incineration of dry sludge (energetic value of obtained dry sludge was 20 MJ/kg or 5.6 kWh/kg) for pre-heating of the incoming sludge, and when the system starts to be continuously used, the calculated SEC will further decrease. If less stringent requirements for water treatment are applicable, an SEC of below 0.8 kWh/L can be achieved. Such results are promising and make this new technology a viable alternative for faecal sludge management.

4.5 OUTLOOK

Faecal sludge management is a rapidly evolving sector. The information described in this chapter is important for developing new technologies, scaling-up and transferring technologies, and optimising established technologies. Experimentation is an iterative process, and research will need to be conducted back and forth between laboratory- and pilot-scale before technologies are ready for full-scale implementation. Projects that incorporate well thought-out experimentation ensure that an appropriate, context-specific treatment solution is selected, instead of assuming that a standard solution will fit. The inherent uncertainties in working with faecal sludge, and with innovative and transferring technologies, make risk management an essential focus in the development and scaling-up of any treatment technology. Risks can be mitigated through dedication to quality experimental design and execution, and through partnerships between municipalities and research institutions, which can help guide experimentation from the start of a project to the optimisation and monitoring of a full-scale FSTP.

Future research needs for scaling-up dewatering and drying technologies will be driven by requirements to optimise treatment technologies that work for faecal sludge. The next advances in dewatering research will include establishing how to more rapidly and cost effectively monitor faecal sludge such that optimal conditioner dosing can be achieved. Another step will be acquiring a fundamental understanding of the processes occurring during stabilisation that affect dewaterability. Future focuses in thermal drying research will address the need for a more holistic understanding of the drying process of faecal sludge, for example morphological changes that occur such as stickiness, and a better understanding of how moisture is bound to faecal sludge.

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Figure 4.27 Settling tests following faecal sludge conditioning experiments at Niayes FSTP, Dakar, Senegal (photo: Eawag).