Chapter 10

Enduse of Treatment Products

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Learning Objectives

- Understand general concerns with resource recovery and how to ensure adequate protection of human and environmental health.
- Know key considerations for determining appropriate methods and rates of the land application of sludge.
- Be able to determine appropriate uses and discharge options for liquid fractions in faecal sludge management.
- Understand the wide range of potential resource recovery opportunities from faecal sludge, and key criteria in selecting the most appropriate options.

10.1 INTRODUCTION

The previous chapters covered how stabilisation, drying, and pathogen reduction of faecal sludge (FS) can be achieved with different treatment technologies, and combinations of these various technologies. Each treatment technology results in endproducts which need to be further treated, disposed of, or harnessed for some type of resource recovery. Endproducts, for example dried or partially dried sludge, compost, leachate, and biogas, each have an intrinsic value, which can turn treatment from merely a method for environmental and public health protection to resource recovery and value creation. This chapter focuses on the endproducts produced from the various FS treatment processes, addresses potential difficulties and restrictions with their enduse, and discusses additional steps that can or should be applied to turn a treatment endproduct into a valuable asset.

Historically, the most common resource recovery from sludge has been as a soil conditioner and organic fertiliser, as excreta contain essential plant nutrients and organic matter that increases the water retaining capacity of soils. There are however several other treatment options that allow for resource recovery. For example, biogas can be produced during anaerobic digestion of FS, with the remaining sludge also being used as a soil conditioner. Novel developments are underway to recover endproducts as a biofuel, for example pyrolysis, gasification, incineration and co-combustion or as resource recovery of organic matter through the growth of Black Soldier flies for protein production.

Table 10.1 Summary of potential resource recovery options from faecal sludge

Produced Product	Treatment or Processing Technology
Soil conditioner	Untreated FS Sludge from drying beds Compost Pelletising process Digestate from anaerobic digestion Residual from Black Soldier fly
Reclaimed water	Untreated liquid FS Treatment plant effluent
Protein	Black Soldier fly process
Fodder and plants	Planted drying beds
Fish and plants	Stabilisation ponds or effluent for aquaculture
Building materials	Incorporation of dried sludge
Biofuels	Biogas from anaerobic digestion Incineration / co-combustion of dried sludge Pyrolysis of FS Biodiesel from FS

This chapter addresses resource recovery options from different FS technologies, both from a biological and an energy point of view, and presents established processes as well as promising innovations.

10.2 RESOURCE RECOVERY OPTIONS

There are a wide range of FS treatment technologies that can be combined in many different ways. All treatment processes result in endproducts which are either treated further, disposed of, or harnessed in some way for resource recovery. The potential use of endproducts should be considered from the initial design phase of any complete FS management (FSM) system, as the treatment technologies used are intrinsically linked to the quality of endproducts generated. A summary of resource recovery options covered in this chapter is provided in Table 10.1.

10.3 GENERAL CONCERNS

With the implementation of resource recovery, it is important to evaluate constituents that may impact both humans and the environment. These include the presence of pathogens and heavy metals. Social factors such as acceptance in using products from FS treatment and market demand also need to be taken into account in order to ensure uptake of the intended enduse.

10.3.1 Pathogens

FS contains large amounts of microorganisms, mainly originating from the faeces. The microorganisms can be pathogenic, and exposure to untreated FS constitutes a significant health risk to humans, either through direct contact, or through indirect exposure. Pathogens are transmitted and spread through an infection cycle, which includes different stages and hosts. The faecal-oral route of transmission is shown in Figure 10.1.

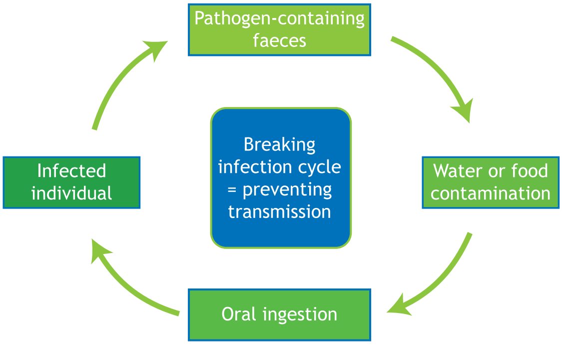

Figure 10.1 Faecal-oral transmission cycle of pathogens.

The transmission cycle of pathogens can be interrupted by putting barriers in place to block transmission paths and prevent cycle completion. FS needs to be treated to an adequate hygienic level depending on the enduse or disposal option. For example, exposure pathways are very different for treated sludge discharged to the environment, compared to sludge used in agriculture, or incinerated. The World Health Organization (WHO) guidelines for safe agricultural practice published in 1998 specified one or less helminth egg/g total solids (TS) for unrestricted irrigation (WHO, 1998). However, the more recent 2006 WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater in Agriculture and Aquaculture places less emphasis on treatment thresholds but rather highlights a multi-barrier approach where lower levels of treatment may be acceptable when combined with other post-treatment barriers along the sanitation chain. This concept of a multi-barrier approach combined with a risk assessment and risk management system to protect public health is explained in detail in the WHO's Safe Use of Wastewater and Excreta, which is available for free via their website (www.who.int/en/) (WHO, 2006).

The first barrier for beneficial use is provided by the level of pathogen reduction achieved through treatment of FS. A selection of further post-treatment barriers 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 and safe food preparation methods such as thorough cooking, washing or peeling. When considering risk of infection all potential exposure groups should be accounted for which can be broadly categorised as workers and their families, surrounding communities and product consumers.

10.3.2 Heavy metals

Heavy metals are a concern due to their toxicity and long-term negative effects on soils. Heavy metals should be evaluated on a case by case basis, but are only a major concern if FS is mixed with industrial effluents that are not adequately pretreated. Heavy metals can also enter the system at the household level through the relatively common practice of improper disposal of wastes containing heavy metals (e.g. batteries, solvents, paints) into the system. The total metals concentration in the sludge differs from the bioavailable metals concentration, as the organic matter in sludge can bind metals in a form that is not biologically available. Because of this effect, sludge is also used for the remediation of metals contaminated sites.

Table 10.2 Regulations for trace element concentrations in the US and Europe for the land application of treated wastewater sludge (biosolids)

Parameters	**Concentration limits (mg/kg)**		
	Exceptional quality (EQ) biosolids (US EPA, 1999)	**Eco label compost (Hogg *et al.*, 2002)**	**Use of biosolids in Spain (Hogg *et al.*, 2002)**
AS	41		
Hg	17		
Fe	nm	–	–
Pb	300	100	750
Ni	420	50	300
Cr	1,200	100	1,000
Cd	39	1	20
Cu	1,500	100	1,000
Zn	2,800	50	2,500
Se	36	–	–

The US Environmental Protection Agency (USEPA) has set limits for heavy metal concentrations for the land application of wastewater sludge based on what is considered a "worst-case scenario" of metal accumulation after 100 years of application. Conservative threshold metal concentrations have been set for the protection of human and environmental health; however, these limits are less conservative than regulations that exist in Europe. An overview of regulatory limits is provided in Table 10.2.

10.3.3 Social factors

Different societies and cultures have different reactions and approaches to the management of human excreta that have to be taken into consideration when evaluating the best enduse for FS. Some cultures reject the use of excreta altogether, whereas others have a long history of excreta use in agriculture. The use of treated FS is however typically perceived differently from excreta, and has a higher acceptance based on its appearance, smell and health impacts. In a society where the use of FS is strictly taboo, other solutions such as co-treatment with other waste streams, use in building materials, or as a fuel might be more appropriate and accepted technologies. This highlights the need for evaluating the market demand of potential endproducts prior to deciding on a treatment and enduse scheme (Diener *et al.*, 2014).

10.4 USE OF FAECAL SLUDGE AS A SOIL CONDITIONER

The use of FS as a soil conditioner can range from deep row entrenchment of untreated FS, to bagged compost that is sold as a commercial product for household level use in horticulture. Using FS as a soil amendment has many benefits over using chemical fertilisers alone (Strauss, 2000). Organic matter in FS can increase soil water holding capacity, build structure, reduce erosion and provide a source of slowly released nutrients. As mentioned above, when using FS as a soil conditioner, the fate of and exposure to pathogens and heavy metals needs to be taken into consideration, and social acceptance can be closely linked to potential commercial value. Other factors that need to be considered include nutrients, which may or may not be available in the ratio required by soil and crop systems.

Table 10. 3 Nutrient content of urine and faeces and mass of nutrients required to grow 250 kg of cereals from Drangert (1998)

Nutrients	Urine[1] (kg)	Faeces[2] (kg)	Total (kg)	Nutrients needed for 250 kg cereals (kg)
Nitrogen (N)	4.0	0.5	4.5	5.6
Phosphorus (P)	0.4	0.2	0.6	0.7
Potassium (K)	0.9	0.3	1.2	1.2
Total amount of N+ P + K	5.3	1.0	6.3	7.5

[1] 500 L/capita/year; [2] 50 L/capita/year

10.4.1 Nutrient content

Theoretically, the quantity of FS produced yearly by a human contains nearly enough plant macro- and micro-nutrients to grow the quantity of food they require in a year (taken as 250 kg of cereals), as shown in Table 10.3.

It is important to determine the appropriate agronomic rate for the land application of treated sludge to maximise benefits, and to prevent environmental contamination from excessive application of nutrients. Nutrients in sludge are present in both organic and inorganic forms. Inorganic forms are more readily available than organic nutrients for plants and microbes to assimilate (e.g. NH_4^+/NH_3, NO_3^-/NO_2^-). Nutrients bound to organic matter are slowly released over time through mineralisation to become biologically available. If nitrogen is applied in excess of plant and soil microbial demand, ammonia can be lost due to volatilisation, and nitrates by leaching through the soil profile. Leaching can lead to the eutrophication of surface waters, and nitrate contamination of drinking water (e.g. resulting in methemoglobinemia).

Many countries have set limits for the land application of FS (e.g. South Africa and China). However, these are typically the maximum allowed rates (i.e. the volume of FS allowed per land area). Estimates for rates of land application can be based on experience; for example, it is estimated that 56 m^3 of FS are required to fertilise one hectare of land when cultivating cereal crops such as maize, millet and sorghum in tropical climates (Asare *et al.*, 2003). However, there are also methods for calculating application rates based on plant nutrient demand, for example, the “Nitrogen Balance” method that is employed with wastewater sludge as illustrated in Figure 10.2 (Henry *et al.*, 1999). Firstly, the amount of nitrogen taken up by plants is calculated by estimating the amount of nitrogen present in the final harvested products. The amount of nitrogen already present in the soil from natural sources is then quantified. The nitrogen required in the land application is the difference between the amount of nitrogen taken up by plants, and the amount supplied by the local natural environment (Henry *et al.*, 1999).

Other research has shown different reactions of crops to nitrogen application rates with compost and co-compost depending on the growth phase of the crops. During the vegetative phase (first 6 weeks) the transpiration efficiency of a maize crop increased up until rates of 150 kgN/ha but then decreased when the nitrogen concentration was increased to 210 kgN/ha (Adamtey *et al.*, 2010). On the other hand, during the reproductive phase (after week 8), the plant’s transpiration efficiency increased with increasing nitrogen application rates (Adamtey *et al.*, 2010). These observations did not apply to soils treated with inorganic fertilisers.

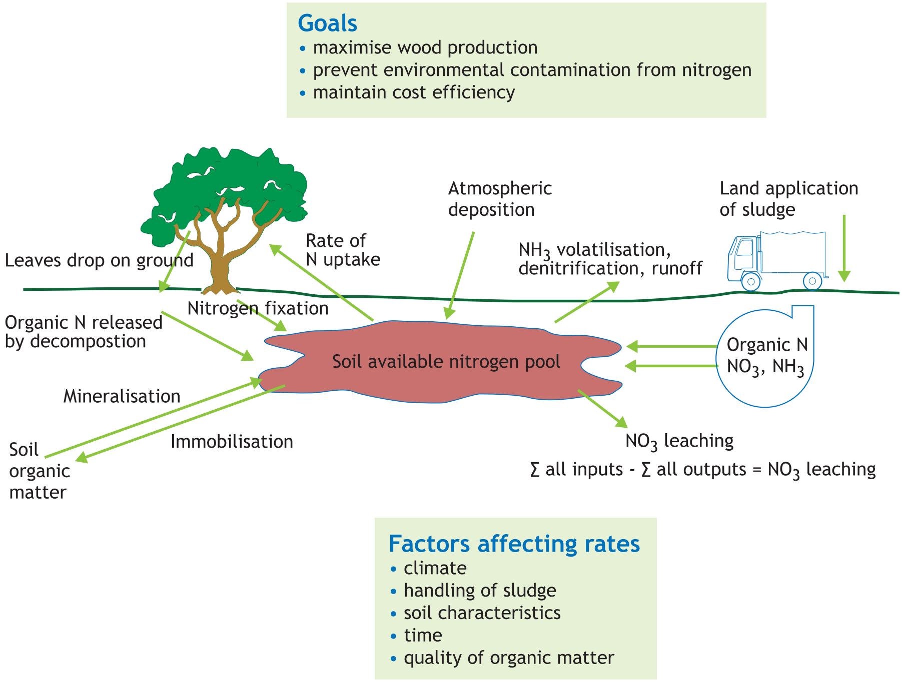

Figure 10.2 Nitrogen balance for the land application of sludge (figure: Linda Strande).

10.4.2 Untreated faecal sludge

Although it is recommended that FS is treated prior to use, some alternatives do exist for the safe disposal and use of FS directly from onsite systems. These options are dependent on the availability of adequate land area, and are therefore not generally appropriate for urban areas. Adequate barriers to pathogen exposure to protect human health are also required.

Deep row entrenchment

One possibility for the direct use of raw FS is deep row entrenchments in forestry applications. By burying sludge in deep ditches, odours are eliminated and the risk of exposure to pathogens is reduced. Trees with a high nitrogen demand are then planted on top of the buried sludge. Deep row entrenchment therefore increases the volume of sludge that can be applied at one time compared to more conventional methods such as spraying on trees or spreading on the soil surface. As with other forms of land application, the appropriate loading of nutrients needs to be considered to prevent environmental contamination. Research on deep row entrenchment of FS is being conducted in forestry trials in South Africa. The research has found that tree growth was improved, and there was no evidence of groundwater contamination (Still and Taylor, 2011). However, the effect on groundwater needs to be further studied, and considered on a case by case basis to ensure environmental protection when using this method. Important factors to consider are soil type and porosity, ground water depth, proximity to drinking water sources, and background nutrient concentrations. There is also long-term experience with deep row entrenchment of wastewater sludge in the US, and this method has been used for the remediation of gravel mining sites for use as tree farms (Kays *et al.*, 2000).

Land application

The direct use of FS has been a long-term practice in parts of China, South-East Asia and Africa. This type of application has the highest level of risk for human health impacts, and is therefore generally not recommended. This practice is best applied in arid to semi-arid regions. It must be ensured that adequate barriers are in place and that there is sufficient land area available. Raw sludge is spread out on farm fields during the dry season, and then incorporated into fields when crops are planted during the rainy season (Cofie *et al.*, 2005). A pit method is also used, where FS is buried with other crop residues and left to mature for a few months prior to use. In areas where this is practiced, there is a large demand for FS. For example, in Northern Ghana, 90% of FS is used as a fertiliser and farmers perceive the competition for FS as one of the main constrains in using it for their crops (Cofie *et al.*, 2005).

10.4.3 Treated faecal sludge in land application

Treatment and processing technologies such as drying beds, composting, and pelletising processes produce treated FS endproducts that can be used as a soil conditioner. The level of remaining pathogens will depend on the selected treatment technology, or combination of technologies.

Sludge from drying beds

The sludge resulting from treatment with planted and unplanted drying beds have very different characteristics, and therefore, different concerns with regards to land application. The majority of helminth eggs are retained in the sludge layer (Cofie *et al.*, 2006). The short retention time of sludge on unplanted drying beds (i.e. weeks) means that further sludge treatment or storage is required if pathogen reduction is to be achieved. The longer retention time of planted drying beds (i.e. years) means that significant pathogen reduction can be achieved, but this needs to be evaluated on a case by case basis. In a study evaluating helminth eggs in planted drying bed sludge, it was found that of 127 eggs/g TS, 6 eggs/g TS were still viable after 7 years (Koottatep *et al.*, 2005a). However, in another study, total eggs decreased from 78.9 to 7.5 eggs/g TS after six months, and viable Ascaris eggs decreased from 38.5 to 4.0 eggs /g TS (Kengne *et al.*, 2009). In addition, due to the long retention time, the treated sludge has similar properties and nutrient content to mature compost.

Information on treatment and removal of sludge from drying beds is covered in Chapters 7 and 8. The amount of sludge that accumulates depends on factors such as the solids content of FS, the loading frequency and the organic loading of the drying bed. With unplanted drying beds, sludge application rates of 100-200 kg TS/m^2/year resulted in a sludge accumulation of 25-30 cm with a 15 day retention time (Cofie *et al.*, 2006). With planted drying beds, sludge application rates of 100, 200 and 300 kg TS /m^2/year resulted in 30-40, 50–70 and 80–113 cm/year respectively (Kengne *et al.*, 2011). Higher loading rates are not recommended, as loadings above 500 kg TS/m^2/year reduce the treatment performance and result in plant wilting (Koottatep *et al.*, 2005b). There is however room for innovation with mixing regimes, application depth and loading rates, and solar/thermal processes.

Co-composting

Co-composting refers to composting of FS together with other waste streams such as municipal solid waste (Figure 10.3). FS with low solids content should be dewatered prior to composting, for example with settling tanks or drying beds. Pathogen reduction is achieved during the composting process through high temperatures, and/or length of time. The properly treated endproduct is a stabilised organic product that may be safely handled, stored and applied to land according to above guidelines for use, without associated concerns of pathogen transmission (Banegas *et al.*, 2007; Koné *et al.*, 2007). For more information on co-composting, refer to Chapters 3 and 5. Although composting is a proven technology to produce a safe to use soil amendment, the local market demand for compost products should be evaluated as compost frequently does not have a significantly high market value. However, other benefits are realised through resource recovery and offsetting disposal costs (Diener *et al.*, 2014).

Figure 10.3 Co-compost of faecal sludge and municipal waste by Sanergy in Nairobi, Kenya (photo: Linda Strande).

Danso *et al.* (2002) evaluated farmers' willingness to pay for compost from municipal solid waste and FS in Ghana. They interviewed 700 farmers in three different cities including both compost users and non-users. Results showed that compost is recognised as a useful resource by most farmers (all compost users and 80% of non-users), and that barriers are more likely to be economic or technical ones rather than cultural. All farmers showed a willingness to pay but at a moderate price, which was too low to achieve a profitable venture if the compost was to be sold at the prices quoted by the farmers. The prices farmers said they were willing to pay varied between 0.1 and 3 USD per 50 kg bag of compost, whereas production costs ranged between 4 and 7 USD per bag (Danso *et al.*, 2002).

Vermicomposting

With vermicomposting, worms breakdown larger organic particles, stimulate microbial activity, and increase the rate of mineralisation, thereby converting FS into humic like substances with a finer structure than normal compost (Alidadi, 2005). Vermicomposting should be operated at a maximum temperature of 35˚C in order to maintain the viability of worms. This temperature is not high enough to ensure pathogen inactivation, so if this is necessary, vermicomposting should be combined with another approach such as storage, or a combination of thermophilic composting and vermicomposting should be used to achieve pathogen reduction (Ndegwa and Thompson, 2000).

Pellets

Dried pellets can be an attractive option for FS processing, producing an endproduct that is easy to transport, has reliable characteristics for enduse, and depending on the level of treatment, is safe for handling. Resource recovery options include use as a soil amendment, or for combustion as a bio-fuel. One example is the LaDePa (latrine dehydration and pasteurisation) process that has been developed in South Africa, and is currently operating in a pilot-scale implementation. The LaDePa process can be used for drier sludges (e.g. dry pit latrines, dewatered sludge), and can also be combined with wastewater sludge that has not had polymers added (Chapter 5). The process involves removal of detritus, followed by drying and infrared radiation, to produce small pellets that can be sold to consumers as a soil amendment (Harrison and Wilson, 2011). Another pellet process being developed in Ghana produces dried pellets which are enriched with urea, so the endproduct has similar fertilising properties of poultry manure. The process involves drying, composting or irradiation for hygienisation, enrichment with urea, and then pelletisation with a binder (Nikiema *et al.*, 2012). One possible concern with the use of dried pellets as a soil amendment is the availability of organic matter and nutrients when applied to soils, but Nikiema *et al.* (2012) have found that the cassava binder they are using is effective for transport stability, and also readily breaks down in the soil.

10.5 USE OF LIQUID STREAMS

Liquid streams from treatment processes can be used for agricultural and horticultural irrigation, or other forms of water reclamation (e.g. non-recreational water features, industrial processes), depending on the quantity produced and the level of treatment. Water reclamation can be beneficial in areas where water resources are limited, and also for nutrient recovery. The main consideration with reclamation of liquid streams is to ensure that the treatment quality is appropriate for its intended use. The same concerns are present as for the use of FS as previously presented. This involves undertaking a human health and environmental risk assessment, followed by a multi-barrier approach to enduse to ensure adequate risk management. With water reclamation, major distinctions are made between planned, unplanned, direct, and indirect usage (Jiménez *et al.*, 2000). Indirect usage implies a diluted waste stream, for example if wastewater or FS has been discharged to a river that is used for irrigation. Direct usage implies it is being obtained directly from the waste source, for example discharging a vacuum truck onto an agricultural field. Planned usage refers to the intended and conscious use, whereas unplanned refers to unknowing or unintentional usage.

This section focuses on the enduse of untreated liquid FS, as well as effluents from FS treatment processes. The concerns associated with liquid FS are slightly different from those with wastewater, as constituents in FS effluents are 10-100 times more concentrated than wastewater. For information specifically on the use of wastewater and wastewater treatment effluent for irrigation, it is recommended that the reader refer to texts such as Wastewater Irrigation and Health (Dreschel *et al.*, 2000) and the WHO's Safe Use of Wastewater and Excreta, both of which are available as free downloads on their websites (www.iwmi.cgiar.org, www.who.int/en/).

10.5.1 Untreated liquid faecal sludge in irrigation

Untreated liquid FS and wastewater are commonly used directly for irrigation in many regions in the world (Figure 10.4). By 'untreated' liquid FS, it is meant liquid streams that are being used directly (e.g. vacuum truck discharge, septic tank effluent), or indirectly where FS cannot be separated from wastewater (e.g. urban areas where excreta and wastewater are discharged directly to water conveyance networks). This practice can provide an essential source of water and nutrients, and is reasonably safe if carried out under controlled conditions. However the possibility for pathogen exposure is high, especially in cases of unplanned, direct use.

Research has been conducted in Ghana on farm-based measures for reducing microbiological health risks (Keraita *et al.*, 2010). Currently, irrigation is being carried out by using untreated water, that is polluted with wastewater, to the direct use of black water, resulting in pathogen contamination of uncooked food crops. The size of agricultural applications ranges from small backyard-scale to medium- to larger-scale vegetable production. Examples of types of on-farm treatment technologies include channels, ponds, wetlands, and filtration (filtration technologies range from sand filtration to passage through cloth media). Appropriate treatment solutions will obviously vary depending on the source and pollution level of water, available land area, climate, tenure of property, and intended use of water (e.g. type of crop, irrigation method). Drip irrigation provides an example of the significant impact that formal irrigation methods can have. Benefits include reduced water usage, and increased yield and human health protection. However, drip irrigation is also one of the more expensive irrigation methods. Areas for future research into the use of liquid FS include understanding the removal of pathogens and recycling of nutrients with different onsite treatment technologies so that treatment outcomes can be reliably predicted and appropriate solutions implemented.

Figure 10.4 Crops grown with faecal sludge settling tank effluent in Yaoundé, Cameroon (photo: Linda Strande).

10.5.2 Treated effluent enduse and disposal

The effluents from FS treatment processes may still contain many constituents of concern, and therefore require further treatment prior to discharge to the environment, or careful evaluation and consideration prior to direct use. Effluents are typically high in nitrogen which is beneficial for the recovery of nutrients, but which can also pose an environmental hazard. Other concerns include pathogens, heavy metals, and salinity.

An example of detrimental effects from high nutrients is demonstrated by pond systems for treatment of settling tank effluent in Ghana, where there was such a high ammonia concentration that algal growth was inhibited (ammonia toxicity to algae starts to occur at 40-50 mg NH_3-N/L). Depending on the influent, loading rates, and operations, the effluent that is discharged from waste stabilisation ponds can have similar characteristics to that achieved with more conventional wastewater treatment processes. Other examples of high constituent concentrations in effluent from FS treatment are unplanted drying bed leachate in Dakar measured at 3,600 mg COD/L, 870 mg BOD/L, 260 mg NH_3-N/L, 370 mg/L TKN, 170 mg NO_3-N/L (Koné *et al.*, 2007), and planted drying beds in Thailand 100-2200 mg COD/L, 6-250 mg TKN/L, and 5-200 mg NH_3-N/L (Koottatep *et al.*, 2005a).

Salinity can interfere with plant growth and have long-term impacts on the soil. The electrical conductivity (EC) observed in effluent from settling tanks in Ghana was 8-10 mS/cm, and leachate from planted drying beds in Thailand 2-5 mS/cm (this high conductivity is mainly due to ammonia). The maximum tolerable conductivity for tolerant plants is at most 3 mS/cm (Koné *et al.*, 2007). Using effluents for irrigation will therefore always increase the salinity of soil in the long-term, and it is recommended that salinity control practices are adopted such as soil washing, providing appropriate soil drainage and controlling salt inputs into the wastewater (WHO, 2006).

Quality standards for treated effluent enduse exist in most countries, but are not necessarily enforced in low- and middle-income countries due to economic limitations. For example, in China, a 95% reduction of helminth eggs needs to be achieved for wastewater effluent enduse, and in Ghana, The Environmental Protection Agency has stipulated more than 90% BOD and faecal removal prior to enduse (Heinss *et al.*, 1998). As discussed for the use of FS as a soil amendment, a better approach for reusing effluent in irrigation is the multi-barrier approach recommended by the WHO. A range

Figure 10.5 Crop irrigation with untreated wastewater is still practiced in many low- and middle-income countries Yaoundé, Cameroon (photo: Linda Strande).

of protective measures depending on the level of treatment should be adopted for human health protection. These include crop restrictions, irrigation technique, harvesting periods, food preparation measures and exposure control (WHO, 2006).

Koottatep *et al.* (2005b) examined the effect of using leachate from planted drying beds for irrigation in a six year study in Thailand where sunflowers were grown under different irrigation conditions. Different plots were irrigated with water containing varying amounts of leachate and the results on plant growth were observed. The experiment showed that sunflower plant growth was not hindered by the leachate, and was in fact improved. The seed and oil yields increased when leachate was used for irrigation (Figure 10.6), the best ratios being 20% and 50% leachate. Slightly lower yields were observed with 100% leachate, probably due to the high salinity leachate.

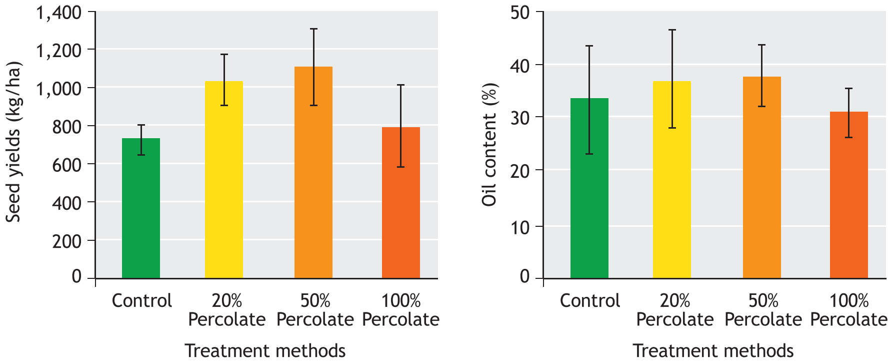

Figure 10.6 Average sunflower seed yields and oil content of sunflower seeds, irrigated with different fractions of drying bed leachate (Koottatep *et al.*, 2005b).

10.6 ADDITIONALFORMS OF RESOURCE RECOVERY

In addition to using endproducts from FS management as soil amendments and for water reclamation, there are many other opportunities for resource recovery depending on the type of treatment and processing technologies. Possibilities include food and agricultural uses (e.g. protein, fodder, fish), or energy reclamation (e.g. biofuels).

10.6.1 Protein

The Black Soldier fly (BSF) larvae (*Hermetia illucens*) can be used as a conventional protein and fat source for poultry and fish feed, and could readily replace fishmeal as a key component of animal feed (St-Hilaire *et al.*, 2007). The larvae grow while feeding on organic matter, such as FS and organic wastes. The last larval stage, the prepupa, has a high protein and fat content. The risks are very low that the BSF is a vector for disease transmission, as it does not feed during the adult stage when it can fly (Sheppard *et al.*, 1994). The use of FS as a feed source for fly larvae has been successfully demonstrated (Nguyen, 2010). However, a mixture of FS and organic municipal waste can achieve higher and faster larvae biomass production (Diener *et al.*, 2009). BSF larvae have the potential of reducing the volume of organic waste by about 55% and the residue remaining after digestion can be composted or anaerobically digested to produce a soil conditioner. It will however be lower in nitrogen and phosphorus than raw organic wastes (Diener *et al.*, 2009). BSF larvae grown only on FS with a dry matter content of 40%, can convert one ton of FS into 20 kg of dried prepupa, with a protein content of 35-44% (Nguyen, 2010). This research is still in developmental stages, and needs to be evaluated on a case by case basis to determine whether the treatment option would be appropriate, if there is a market for endproducts, and if other factors such as climate and availability of organic matter are conducive to the growth of BSF.

10.6.2 Fodder and plants

The plants used in drying beds should be harvested regularly to aid in sludge removal, but can also be harvested more frequently because they have a commercial value that can generate additional revenue. Uses of plants from drying beds include ornamental arrangements, use in compost, or as fodder for livestock (Case Study 10.1). The choice of plants to be grown on the beds should be selected taking the local conditions and market into consideration. In this way, the species that will grow well in drying beds, and which have the potential to generate the most income will be planted (for more information refer to Chapter 8). The growing of plants on drying beds have also been shown to have an increased productivity compared to traditional growing methods. For example, more than 900 shoots/m^2 of Echinochloapyramidalis have been reported with full scale planted dewatering beds in Dakar after 21 weeks of growth (Tine *et al.*, 2009), and in Cameroon, up to 150 dry tons/ha/year (approximately 750 fresh tons /ha/yr) of E. pyramidalis were reported (Kengne *et al.*, 2008).

Case Study 10.1 : Market value of fodder grown in drying beds in Cameroon

A socio-economic survey conducted in three cities of Cameroon (Douala, Yaoundé and Garoua) to assess the market potential of *E. pyramidalis* has shown that the daily quantities of marketed forage vary between 5 and 8 tons of fresh weight in the dry and rainy season respectively (Figure 10.7). This fodder plant is used by breeders to feed horses, goats, sheep, dairy cows, rabbits, greater cane rats (*Thryonomys swinderianus*) and guinea pigs (Figure 10.8).

Figure 10.7 Antelope grass is a highly prized fodder in urban and peri-urban areas (photo : Ives Kengne).

E. pyramidalis is marketed in the urban and peri-urban centres and the price varies throughout the year according to its quality (dry or fresh), quantity and availability. Prices obtained varied according to the seasons from 0.1–0.2 USD to 0.2–0.3 USD/kg fresh weight, generating a daily income varying between 500–1,000 USD and 1,600–2,400 USD in dry and rainy seasons, respectively.

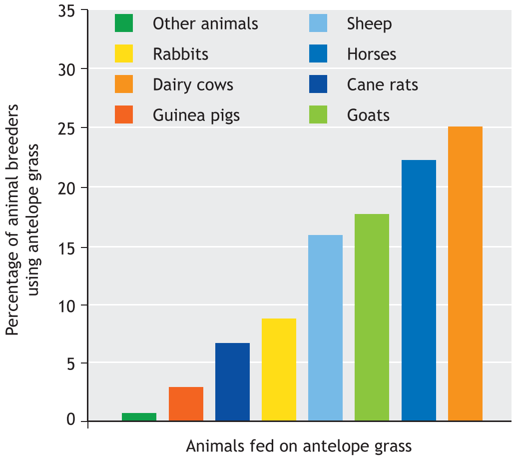

Figure 10.8 Range of animals being fed on *E. pyramidalis* (antelope grass) in Yaoundé, Cameroon.

10.6.3 Fish and plants

The nutrients in FS can be harnessed for use in aquaculture, when growing fish in stabilisation ponds with the effluent from FS treatment plants. The nutrients can increase the growth of plankton, or increase the growth of aquatic plants such as duckweed, water spinach, or water mimosa. Plankton can be harvested for use as fish feed in aquaculture, and aquatic plants can be harvested for animal feed or human consumption. Fish bred in ponds with FS can be used as animal feed, and are also sometimes used for direct human consumption. In the case of direct consumption, certain precautions have to be taken to prevent pathogen transmission and adverse health effects.

Although fish are not susceptible to human pathogens, they can be carriers of them. Faecal bacteria can accumulate in the internal organs and gills of fish. Protective barriers to prevent transfer to humans include cooking fish thoroughly before consumption, transferring the fish into clean water ponds for 2 to 3 weeks before consumption, or maintaining a faecal coliform count of less than 1,000 FC/100mL (WHO, 1998). Fish can also act as intermediate hosts to *Helminths*, which is a concern with FS. In areas where *schistosomiasis* is endemic, fishery workers may be exposed to snails, which are vectors of the disease. Preventive measures include using treated FS, wearing protective clothing such as boots, and removing vegetation on the banks of the ponds to reduce snail growth (Cairncross and Feachem, 1983).

Another concern is that there is inadequate knowledge of the technical aspects of using FS or wastewater in aquaculture, thereby making control of operating parameters more of an art than a science, and leading to potential problems such as the rapid eutrophication of ponds due to excess nutrients.

10.6.4 Building materials

Dried FS can be used in the manufacturing of cement and bricks, and in the production of clay-based products. This resource recovery option captures the material and chemical properties of FS, at a trade-off of their nutrient value not being utilised. The presence of pathogens is less of a concern as human contact is reduced, and high manufacturing temperatures result in the killing off of pathogens.

Dried wastewater sludge and FS have been shown to have similar qualities to other traditional raw building materials such as limestone and clay materials (Jordán *et al.*, 2005; Lin *et al.*, 2012). FS is commonly used in cement production in Japan as an alternative fuel in the kiln, and/or by incorporating the ash resulting from FS incineration into the cement (Taruya *et al.*, 2002).

Another possible method of integrating FS into cement manufacturing is to stabilise and dry the sludge through treatment with lime. Rodriguez *et al.* (2011) describe a process where 20 to 30% lime (CaO) is added to wastewater sludge, which triggers degradation of organic matter and hydration of the CaO. The reaction between lime and the sludge is exothermic and therefore favours sludge drying (the temperature increases from 20°C to 100°C). The product obtained after lime treatment has a powder-like texture with a particle size smaller than 40 μm and can be used as a raw material instead of limestone in cement manufacturing (Rodríguez *et al.*, 2011).The authors claim that this form of sludge dewatering is more energy efficient than other processes due to the exothermic reaction of lime and sludge generating enough heat to promote evaporation without requiring the use of fossil fuels.

FS can also be used in the manufacture of ceramics. Experiments carried out by Jordan *et al.* (2005) showed promising results for the incorporation of FS into the ceramic processing mixture. Amounts of dried sewage sludge varying from 1-10 wt.% were incorporated in the manufacture of clay. Results showed that the addition of wastewater sludge increased the permeability of clay, and reduced its bending strength (Jordán *et al.*, 2005).

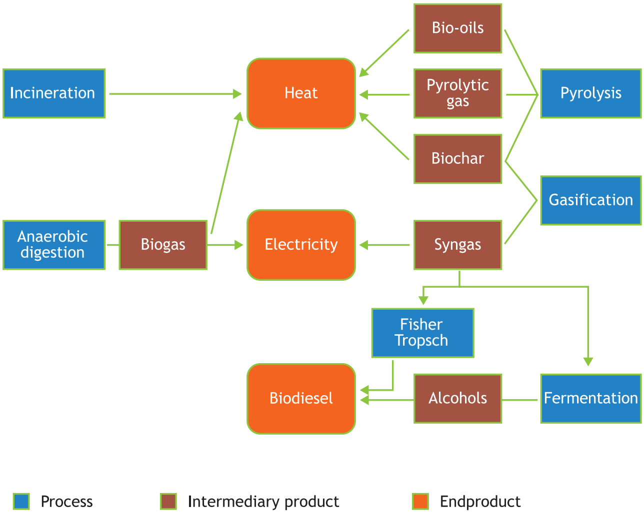

Figure 10.9 Energy recovery options from faecal sludge.

10.6.5 Biofuels

As summarised in Figure 10.9, there are several biological and thermal options for the production of energy from FS. These technologies have been receiving increased interest due to the considerable demand for sustainable biofuels. Possible technologies include anaerobic digestion, which yields biogas, heat, and digestate (sludge); pyrolysis or gasification, which yields biochar, oils and gasses; biodiesel, which can be produced through fermentation or successive chemical reactions; and incineration or co-combustion of dried FS. Energy recovery harnesses the energy potential of organic matter in FS, but frequently at a trade-off of nutrient recovery.

Biogas

The anaerobic digestion of FS produces a mixture of gaseous compounds, commonly referred to as ‘biogas’. The mixture of gasses that is commonly produced is presented in Table 10.7. The mixture and amount of gas produced depends on operating parameters such as stability of the sludge, COD of the sludge, and temperature. Biogas has a high energy content due to the high calorific value of methane

Table 10.7 Gases produced during anaerobic digestion (adapted from Bates, 2007)

Substance	Symbol	Percentage (%)
Methane	CH_4	50-70
Carbon dioxide	CO_2	30-40
Hydrogen	H_2	5-10
Nitrogen	N_2	1-2
Water vapour	H_2O	0.3
Hydrogen sulphide	H_2S	Traces

Table 10.8 Biogas fuel equivalents at 15°C and atmospheric pressure (adapted from Bates, 2007)

Energy Source	Equivalent to 1m^3 of biogas
Petrol	0.53 - 0.75 L
Diesel	0.48 - 0.68 L
Firewood	1.50 kg
Electricity	1.51 kW/h
LPG	0.46 kg

and can therefore be used as a fuel. The gas can be used directly for applications such as cooking fuel, but if used in engines should be 'scrubbed' prior to use to remove the hydrogen sulphide to avoid corrosion. Table 10.8 presents equivalents of common fuels compared to 1 Nm^3 of biogas. Large and small scale anaerobic digestion facilities have the same equipment requirements, the cost of which can sometimes be prohibitive for small scale applications. Smaller scale applications also tend to be more sensitive to shock loadings and process changes than larger scale plants, making the latter easier to manage. Electricity generation from biogas is not always practical on a small scale. For example, the anaerobic digestion of organic waste generates about 100-200 Nm^3 of biogas per ton of municipal organic waste (Claassen *et al.*, 1999). Taking a 25% conversion efficiency of biogas into electricity, 1m^3 of biogas can generate 1.51 kWh (Cuéllar and Webber, 2008). Therefore the anaerobic digestion of one ton of municipal organic waste could produce a maximum of about 320 kWh, which is sufficient to operate one 100 W light bulb for around 132 days, or 3,200 100 W light bulbs for 1 hour. In this case it would be more feasible to use the biogas as a cooking gas (or as a fuel) for local district lighting.

The solids fraction remaining after anaerobic digestion can also be utilised for any of the enduses described for FS, but may require further treatment depending on the choice. The degree of pathogen destruction during anaerobic digestion depends on the operating temperature. Thermophilic digestion (>50ºC) will result in significant pathogen reduction, but mesophilic conditions (30-38ºC) do not guarantee pathogen inactivation. Maintaining a well-mixed reactor also increases the degree of pathogen deactivation as it prevents the formation of dead zones in the reactor (Smith *et al.*, 2005).

Incineration/co-combustion

Incineration is the complete combustion of organic matter at high temperatures, and can either be a disposal mechanism, or provide a way to generate electricity or heat. Incineration of wastewater sludge is relatively common in Europe and US. Incineration reduces sludge to ash (10% of its initial volume) which is mainly composed of remaining inorganic material, and at the same time destroys all pathogens due to the high processing temperatures (Werther and Ogada, 1999). Several methods of incineration and co-combustion are possible with FS and these are summarised in Figure 10.10. Ashes remaining after incineration can either be disposed of, or utilised as raw materials for the manufacture of construction materials.

The calorific value of wastewater sludge typically ranges from 10-29 MJ/kg, while the calorific value of FS is reported to be 17 MJ/kg solids; compared to an average coal value of 26 MJ/kg (Murray Muspratt *et al.*, 2014). Sludge can be co-combusted with coal in coal-fired power plants or other industrial applications such as cement kilns (Figure 10.11; Rulkens, 2008). The direct injection of dewatered FS can reduce NO_x emissions from a cement kiln by 40% and produces 30% less CO_2 emissions compared to when sludge is incinerated (Taruya *et al.*, 2002). The use of FS as a fuel will only be financially sustainable if the financial gains outweigh the economic and environmental costs of sufficient drying prior to combustion.

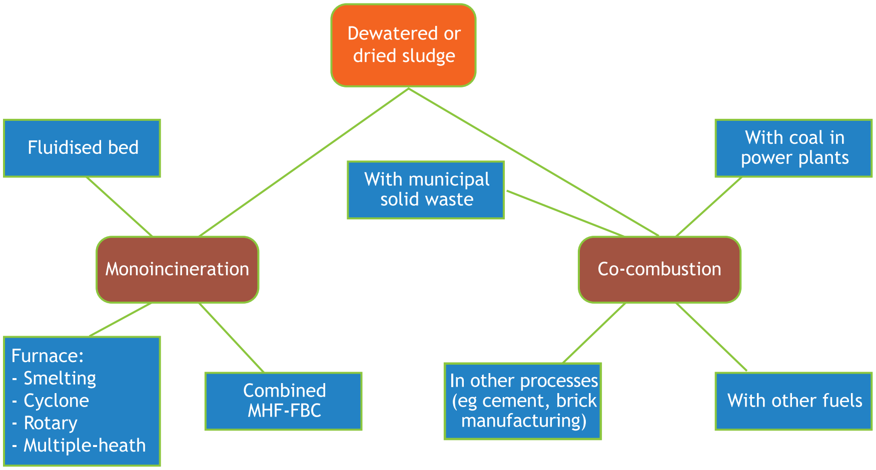

Figure 10.10 Different options for the combustion of sludge (adapted from Werther and Ogada, 1999).

Incineration can produce gases that contain pollutants which can enter the atmosphere. A gas treatment system for the removal of pollutants prior to off-gassing is typically very expensive (Rulkens, 2008). Despite the high nitrogen content of FS, it has been shown that the emissions of nitrous oxides are in fact lower from sludge incineration than from coal incineration. The emissions of dioxins and furans from sludge incinerators are also lower than from waste incinerators (Werther and Ogada, 1999).

Pyrolysis/gasification

Pyrolysis is based on the principle of heating in an oxygen-depleted environment. The absence of oxygen prevents combustion from occurring, and hence yields carbon-based endproducts that are different from those produced during incineration. These endproducts include (bio)char, oils and gases, the quantity of each depending on the processing temperature and presence of gasifying agents. At temperatures above 700°C gasification occurs, which favours the production of syngas (H_2 and CO), whereas temperatures between 350-500°C results in pyrolysis, thereby yielding a larger quantity of char, and gas with more compounds (e.g. CO_2 and CH_4). Both endproducts can be used as fuels, and the gasses produced can also be recovered (Rulkens, 2008). Reported calorific values for syngas from the gasification of wastewater sludge are similar to that produced from coal (7-9.5 MJ/m^3) (Domínguez *et al.*, 2006).

Figure 10.11 FaME (Faecal Management Enterprises) project pilot scale kiln for combustion of faecal sludge to heat oil in industrial processes, Thies Polytechnical University, Senegal (photo: Linda Strande).

Char can be used in furnaces and kilns in the same way as coal, but an energy analysis should be considered to ensure that the production of char from wet sludge has a net positive energy gain. Char can also be used as a soil conditioner; however, there is still some debate around the benefits. As char is a highly porous material, it is thought that this will increase the surface area in soils, and hence improve water retention and aeration capacity (Chan *et al*., 2007). This technique is commonly compared to the 'terra preta' soils in the Amazon resulting from usage patterns of ancient civilisations. However, char does not provide available organic matter and nutrients present in compost as these are lost in the pyrolysis or gasification process. Growing trials with char have shown both plant yield suppression and plant yield increases. Char can also potentially deplete nutrients in the soil if they are absorbed (Brown, 2011). It therefore appears that it is more beneficial to use char as a fuel than a soil conditioner. There is however a need for additional research to further characterise the properties of char, the dependence on manufacturing conditions, and the effects on soil (Manyà, 2012). To date, information is only available based on wastewater sludge (biosolids) and not with FS, although research is currently being conducted as part of the Reinventing the Toilet Challenge (RTTC) programme of BMGF.

Conventional pyrolysis is carried out with relatively dry materials (Figure 10.12), whereas hydrothermal carbonisation (HTC) is a different type of pyrolysis that allows handling of wet materials. Hydrothermal carbonisation or hydrous pyrolysis is the thermal degradation of biomass in the presence of subcritical water and in the absence of oxygen (Libra, 2011). The solid yielded from this process is referred to as hydrochar to distinguish it from char obtained from dry pyrolysis. Hydrochar is reported to have a highly porous nanostructure, which can be utilised for ion binding, pollutant or water absorption, or as a scaffold for particle binding of catalysts (Titirici *et al*., 2007). Berge *et al*. (2011) produced hydrochar from anaerobically digested wastewater sludge and found that its carbon content was lower than the initial feedstock, indicating an ineffective carbonisation. Possible reasons reported for this are an incomplete initial hydrolysis step, the slightly basic pH of digested sludge and its stabilised state, and being less prone to changes in carbon content (Berge *et al*., 2011). Further research is required in the field of HTC and its applications to biomass degradation. Overall, there is less literature available on HTC than dry pyrolysis and char, probably due to the intense research interest that the discovery of the ‘terra preta’ soils instigated in char research (Berge *et al.*, 2011), and the high energy and pressure requirements of HTC.

Gasification is made up of a series of chemical and thermal steps: drying, pyrolysis, oxidation and reduction (Dogru *et al.*, 2002). This process mainly produces a synthetic gas, or syngas, which is made up of carbon monoxide (CO), carbon dioxide (CO_2), hydrogen gas (H_2) and other trace elements. Syngas has a high energy content and can be either directly used for electricity generation in gas engines and turbines, or it can be further processed to obtain liquid fuel. It has been reported that gasification yields 37% more energy than pyrolysis (Nipattummakul *et al.*, 2010). Dogru *et al.*, (2002) obtained gas with a calorific value of 4 MJ/m^3 in a bench-scale experiment with a fixed bed downdraft gasifier. The use of this type of gasifier is limited to small scale applications as it cannot be easily scaled up, whereas circulating fluidised bed configurations, most commonly used for coal applications, are planned to be used on an industrial scale for wastewater sludge gasification (Ferrasse *et al.*, 2003).

Hydrogen gas is potentially a valuable renewable fuel, which has the potential to power hydrogen fuel cells or hydrogen engines without greenhouse gas emissions. Under the right operating conditions, hydrogen can make up a substantial portion of the syngas that is produced, and research efforts are focused on optimising processing conditions to maximise hydrogen gas yield. Greater volumes of hydrogen gas can be obtained with higher reactor temperatures, and three times as much hydrogen can be obtained with steam gasification of sewage sludge than with air gasification (0.076 g gas/sample at 1,000°C) (Nipattummakul *et al.*, 2010).

Figure 10.12 Iiribogo gasification project utilising corn husks and sawdust, located in Muduuma Sub-county, Mpigi District, Uganda (photo: Linda Strande).

Other alternatives for biofuel production include the processing of syngas into transportation fuel. Syngas can be fermented to produce alcohols such as ethanol. This fermentation is mediated by microorganisms, which convert syngas into hydrocarbons. These microorganisms are mesophilic and the gases therefore need to be cooled down b efore the fermentation step. Heat recovery during the cooling process is possible (Henstra *et al*., 2007). Another option is to apply the Fischer Tropsch process to syngas to obtain biodiesel, which involves a chain of chemical reactions aided by a metal catalyst (e.g., cobalt, iron, ruthenium). This process is complex, and applications of producing liquid hydrocarbons from biomass are only in the first stages of commercialisation (Srinivas *et al*., 2007).

Biodiesel

Biodiesels are produced from oils and fats, and therefore the lipids contained in FS have to be harvested through extraction processes. Once lipids are isolated, they undergo a base- or acid-catalysed trans esterification process using alcohol. The resulting compounds are fatty acid alkyl esters (i.e. methyl, propyl or ethyl), which make up the biodiesel. The difficulty in maximising the extraction of lipids from sludge and the associated costs are the main barriers to producing biodiesel from FS (Kargbo, 2010).

Biodiesel can be used in similar applications to conventional fossil fuel-based diesel. Biodiesel has a slightly lower heat of combustion than petroleum-based diesel, resulting in about a 10% reduction in power when using biodiesel. Also It does however have benefits compared to conventional diesel such as increasing engine life and producing less exhaust gas emissions (Demirbas, 2009).

Figure 10.13 Screenings from the Niayes faecal sludge treatment plant in Dakar, Senegal (photo: Linda Strande).

10.7 GRIT SCREENINGS

Screening at the influent of treatment plants is essential to prevent clogging of pumps and machinery, and to prevent detritus in endproducts (Figure 10.13). Unfortunately, there are not many options for resource recovery from these screening solids. The screenings contain a large number of pathogens, are odorous, haves a high water content, and a high density and weight. Organic decomposable wastes represent the largest constituent of screenings from FS, as also observed for municipal solid wastes in low-income countries (Troschinetz and Mihelcic, 2009). Screenings also contain rocks, sand, iron, wood, textiles and plastics in various proportions.

The most common form of disposal is landfilling. Incineration is usually not an option due to the presence of non-decomposable materials in the screenings (e.g. rocks, sand). Composting is an option to treat the organic decomposable fraction, potentially co-composted with domestic household solid wastes to provide sufficient readily degradable matter (Koné *et al*., 2007, Niwagaba, 2009).

10.13 BIBLIOGRAPHY

Adamtey, N., Cofie, O., Ofosu-Budu, K.G., Ofosu-Anim, J., Laryea, K.B., Forester, D. (2010). Effect of N-enriched co-compost on transpiration efficiency and water-use efficiency of maize (zea mays L.) under controlled irrigation. Agricultural Water Management 97, p. 995-1005.

Alidadi, H., Parvaresh, A.R., Shamansouri, M.R., Pourmoghodas, H., Najafpoor, A.A. (2005). Combined compost and vermicomposting process in the bioconversion of sludge. Iranian Journal of Environmental Health Science & Engineering 2, p.251-254.

Asare, I., Kranjac - Berisavjevic, G., Cofie, O. (2003). Faecal Sludge Application for Agriculture in Tamale. Urban Agricultural Magazine 10, p.32-33.

Banegas, V., Moreno, J, L., Garcia, C., Leon, G., Hernandez, T. (2007). Composting anaerobic and aerobic sewage sludges using two proportions of sawdust. Waste Management 27, p.1317-1327.

Bates, L. (2007). Technologies that really work. Boiling Point 53. Available from http://stoves.bioenergylists.org/taxonomy/term/790.

Berge, N, D., Ro, K. S., Mao, J., Flora, J. R.V., Chappell, M. A., Bae, S. (2011). Hydrothermal carbonization of municipal waste streams. Environmental Science & Technology 45(13), p.5696-5703.

Brown, S.L. (2011). Climate change connections: Real Solutions Fill The Vacuum. Biocycle 52(1), p.51-56.

Cairncross, S., Feachem, R. (1983). Health aspects of waste re-use. Environmental Health Engineering in the Tropics. Second edition edn. p.205-213.

Chan, K.Y., van Zwieten, L., Meszaros, I., Downie, A., Joseph, S. (2007). Agronomic values of greenwaste biochar as a soil amendment. Soil Research 45(8), p.629-634.

Claassen, P.A. M., van Lier, J.B., Lopez Contreras, A.M., van Niel, E. W. J., Sijtsma, L., Stams, A.J.M., de Vries, S.S. Weusthuis, R.A. (1999). Utilisation of biomass for the supply of energy carriers. Springer Berlin/Heidelberg.

Cuéllar, A, D., Webber, M,E. (2008). Cow power: the energy and emissions benefits of converting manure to biogas. Environmental Research Letters 3.3.

Cofie, O.O., Agbottah, S., Strauss, M., Esseku, H., Montangero, A., Awuah, E., 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), p.75-82.

Cofie, O.O., Kranjac-Berisavljevic, G.,Drechsel, P.(2005).The use of human waste for peri-urban agriculture in Northern Ghana. Renewable Agriculture and Food Systems 20(2), p.73.

Danso, G., Fialor, S.C., Drechsel, P.(2002). Farmers' perception and willingness-to-pay for urban waste compost in Ghana. In: Almorza, D., Brebbia, C., Sales, D., Popov, V., eds, Waste Management and the Environment. Southampton: WIT Press, p.231-241.

Demirbas, A. (2009). Progress and recent trends in biodiesel fuels. Energy Conversion and Management 50(1), p.14-34.

Diener, S., Semiyaga, S., Niwagaba, C., Muspratt, A., Gning, J.B., Mbéguéré, M., Ennin, J.E., Zurbrugg, C., Strande, L. (2014). A value proposition: resource recovery from faecal sludge – can it be the driver for improved sanitation? Resources Conservation & Recycling (in press).

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

Domínguez, A., Menendéz, J.A., Inguanzo, M., Pís, J.J. (2006). Production of bio-fuels by high temperature pyrolysis of sewage sludge using conventional and microwave heating. Bioresource technology 97(10), p.1185-1193.

Dogru, M., Midilli, A., Howarth, C.R. (2002). Gasification of sewage sludge using a throated downdraft gasifier and uncertainty analysis, Fuel Processing Technology 75, p.55–82.

Drangert, J-O. (1998). Fighting the urine blindness to provide more sanitation options. Water SA 24(2) p.157-164.

Dreschel, P., Scott, C., Raschid-Sally, L., Redwood, M., Bahri, A. (2000). Wastewater Irrigation and Health: Assessing and Mitigating Risk in Low-income Countries. Earthscan, IWMI, and IDRC.

Ferrasse, J.-H., Seyssiecq, I., Roche, N. (2003) Thermal gasification : a feasible solution for sewage sludge valorisation? Chemical Engineering and Technology 23 (9), p.941-945.

Harrison, J., Wilson, D. (2011). Towards Sustainable Pit Latrine Management Through LaDePa, WISA 2012, 2011.

Heins, U., Larmie, S.A., Strauss, M. (1998). Solids Separation and Pond Systems for the Treatment of Faecal Sludges in the Tropics.05/98. Dubendorf, Switzerland: EAWAG/SANDEC.

Henry, C., Sullivan, D., Rynk, R., Dorsey, K., Cogger, C. (1999). Managing nitrogen from biosolids. Seattle: Washington State Department of Ecology.

Henstra, A.M., Sipma, J., Rinzema, A., Stams, A.J. (2007). Microbiology of synthesis gas fermentation for biofuel production. Current Opinion in Biotechnology 18(3), p.200-206.

Hogg, D.,Barth, J., Favoino, E., Centemero, M., Caimi, V., Amlinger, F., Devliegher, W., Brinton, W., S. Antler, S. (2002). Comparison of compost standards within the EU, North America and Australasia. The Waste and Resources Action Programme, Oxon, UK, p.1-97.

Jimenez, B., Chavez, A., Barrios, J. E., Perez, R. (2000). Impact and potential of reused water in the Mezquital Valley, Water 21, p.34-36

Jordan, M. M., Almendro-Candel, M. B., Romero, M., Rincón, J. M. (2005). Application of sewage sludge in the manufacturing of ceramic tile bodies. Applied Clay Science 30(3–4), p.219-224.

Kargbo, D.M. (2010). Biodiesel Production from Municipal Sewage Sludges. Energy and Fuels 5, p.2791-2794.

Kays, J.S., Flamino, E.J., Felton, G., Flamino, P.D. (2000). Use of deep-row biosolids applications to grow forest trees: a case study. In C.L. Henry, R.B. Harrison, R.K. Bastian (Eds.). The Forest Alternative: Principles and Practice of Residuals Use, p.105-110. Seattle, WA: University of Washington College of Forest Resources.

Kengne, I.M., Kengne, E.S., Akoa, A., Bemmo, N., Dodane, P.-H., Koné, D., (2011). Vertical-flow constructed wetlands as an emerging solution for faecal sludge dewatering in developing countries. Journal of Water, Sanitation and Hygiene for Development 1(1), p.13-19.

Kengne, I.M., Akoa, A.A., Soh, E.K., Tsama, V., Ngoutane, M.M., Dodane, P.H., Koné, D. (2008). Effects of faecal sludge application on growth characteristics and chemical composition of Echinochloa pyramidalis (Lam.) Hitch. and Chase and Cyperus papyrus L. Ecological Engineering 34(3), p.233-242.

Kengne, I.M., Akoa, A., Koné, D. (2009). Recovery of biosolids from constructed wetlands used for faecal sludge dewatering in tropical regions. Environmental Science and Technology 43(17), p.6816-6821.

Keraita, B., Konradsen, F., Drechsel, P. (2010). Farm-based measures for reducing microbiological health risks for consumers from informal wastewater-irrigated agriculture. In: Drechsel, P., Scott, C., Raschid-Sally, L., Redwood, M., Bahri, A. Wastewater Irrigation and Health: Assessing and Mitigating Risk in Low-income Countries. London: Earthscan. p.189-208.

Koné, D., Cofie, O., Zurbrugg, C., Gallizzi, K., Moser, D., Drescher, S., Strauss, M. (2007). Helminth eggs inactivation efficiency by faecal sludge dewatering and co-composting in tropical climates. Water Research 41(19), p.4397-4402.

Koottatep, T., Polprasert, C., Hadsoi, S. (2005a). Nutrient Recycling and Treatment of Faecal Sludge through Constructed Wetlands and Sunflower Plant Irrigation, Proceedings of the International Forum on Sustainable Techniques for Wastewater Management between Thailand and Taiwan ROC, p.26-29.

Koottatep, T., Surinkul, N., Polprasert, C., Kamal, A.S.M., Koné, D., Montangero, A., Heinss, U., Strauss, M. (2005b). Treatment of septage in constructed wetlands in tropical climate: lessons learnt from seven years of operation. Water Science and Technology 51(9), p.119-126.

Libra, J.A., Kyoung, S.R., Kammann, C., Funke, A., Berge, N.D., Neubauer, Y., Titirici, M.M., Fühner, C., Bens, O., Kern, J., Emmerich, K.-H. (2011). Hydrothermal carbonization of biomass residuals: a comparative review of the chemistry, processes and applications of wet and dry pyrolysis, Biofuels 2(1), p.89–124.

Lin, Y., Zhou, S., Li, F., Lin, Y. (2012).Utilization of municipal sewage sludge as additives for the production of eco-cement. Journal of Hazardous Materials, 213–214, p.457-465.

Manyà, J. J. (2012). Pyrolysis for Biochar Purposes: A Review to Establish Current Knowledge Gaps and Research Needs. Environmental Science and Technology 46 (15), p.7939–7954.

Murray Muspratt, A., Nakato, T., Niwagaba, C., Dione, H., Baawuah, N., Kang, J., Stupin, L., Regulinski, J., Mbéguéré, M., Strande, L. (2014). Fuel Potential of Faecal Sludge: Calorific Value Results from Uganda, Ghana, and Senegal. Journal of Water Sanitation and Hygiene for Development, in press.

Ndegwa, P.M., Thompson, S.A. (2000). Effects of C-to-N ratio on vermicomposting of biosolids, Bioresource Technology 75(1), p.7-12.

Nguyen, H.D. (2010). Decomposition of organic wastes and fecal sludge by black soldier fly larvae. School of Environment, Resources and Development. Asian Institute of Technology, Thailand, p.75.

Nikiema, J., Cofie, O., Impraim, R., Dreschel, P. (2012). Fortified Excreta Pellets for Agriculture. Conference Proceedings – 2nd International Faecal Sludge Management Conference, Durban, South Africa, October 29-31, 2012.

Nipattummakula, N., Ahmeda, I., Kerdsuwan, S., Guptaa, A. K. (2010). High temperature steam gasification of wastewater sludge. Applied Energy 87(12), p.3729-3734.

Niwagaba, C. (2009). Treatment technologies for human faeces and urine. PhD Thesis, Doctoral Thesis No. 2009: 70. Swedish University of Agricultural Sciences, Uppsala, Sweden. ISBN 978-91-576-7417-3.

Rulkens, W. (2008). Sewage Sludge as a Biomass Resource for the Production of Energy: Overview and Assessment of the Various Options. Energy & Fuels 22(1), p.9-15.

Rodríguez, N.H., Granados, R.J., Blanco-Varela, M.T., Cortina, J.L., Martínez-Ramírez, S., Marsal, M., Guillem, M., Puig, J., Fos, C., Larrotcha, E., Flores, J. (2011). Evaluation of a lime-mediated sewage sludge stabilisation process. Product characterisation and technological validation for its use in the cement industry. Waste Management 32(3), p.550-60.

Sheppard, C.D., Newton, L.G., Thompson, S.A., Savage, S. (1994). A value added manure management system using the black soldier fly. Bioresource Technology 50(3), p.275-279.

Smith, S.R., Lang, N.L., Cheung, K.H.M., Spanoudaki, K. (2005). Factors controlling pathogen destruction during anaerobic digestion of biowastes. Waste Management 25(4), p.417-425.

Srinivas, S., Malik, R.K., Mahajani, S.M. (2007). Fischer-Tropsch synthesis using bio-syngas and CO_2. Energy for Sustainable Development 11(4), p.66-71.

St-Hilaire, S., Sheppard, C., Tomberlin, J.K., Irving, S., Newton, L., McGuire, M.A., Mosley, E.E., Hardy, R.W., Sealey, W. (2007). Fly Prepupae as a Feedstuff for Rainbow Trout, Oncorhynchus Mykiss. Journal of the World Aquaculture Society 38(1), p.59-67.

Still, D., Taylor, C. (2011). Simple sludge disposal with benefits? Deep-row entrenchment with agroforestry. What happens when the pit is full? FSM Seminar report, 14-15 March 2011, WINSA, p.29-30.

Strauss, M. (2000). Human Waste (Excreta and Wastewater) Reuse. ETC/SIDA Bibliography on Urban Agriculture. Duebendorf, Switzerland: EAWAG/SANDEC.

Taruya, T., Okuno, N., Kanaya, K. (2002). Reuse of sewage sludge as raw material of Portland cement in Japan. Water Science and Technology 46(10), p.255-258.

Tine D., 2009. Traitement de boues de vidange de systèmes d’assainissement autonome à Dakar (Sénégal) : Etude d’une phase d’acclimatation de deux espèces utilisées pour le traitement des boues de vidange domestiques. Mémoire de DEA en Sciences de l’environnement. Institut des Sciences de l’Environnement, Université Cheikh Anta Diop de Dakar

Titirici, M.M., Thomas, A., Antonietti, M. (2007). Back in the black: hydrothermal carbonization of plant material as an efficient chemical process to treat the CO_2 problem? New Journal of Chemistry 31(6), p.787-789.

Troschinetz, A.M., Mihelcic, J.R. (2009). Sustainable recycling of municipal solid waste in developing countries. Waste Management 29(2), p.915-931.

US EPA (1999). Biosolids Generation, Use, and Disposal in The United States. U.S. Environmental Protection Agency Municipal and Industrial Solid Waste Division Office of Solid Waste EPA 530-R-99-009. Available from http://www.epa.gov/compost/pubs/biosolid.pdf.

Werther, J.,Ogada, T. (1999).Sewage sludge combustion. Progress in Energy and Combustion Science 25(1), p.55-116.

WHO (2006). WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater - Volume IV: Excreta and greywater use in agriculture. World Health Organization (WHO), Geneva, Switzerland

Yadave, L.S., Hesse, P.R. (1981): The Development and Use of Biogas Technology in Rural Areas of Asia (A Status Report 1981). Improving Soil Fertility through Organic Recycling. Food and Agriculture Organization (FAO) and United Nations Development Program (UNEP).

End of Chapter Study Questions

1. Identify at least six resource recovery options for FS, the associated treatment technologies, and their advantages and disadvantages.

2. Describe different options for composting and their advantages and disadvantages.

3. Char from FS could be used as a soil conditioner or as a fuel. List advantages and disadvantages for both resource recovery options.