Environmental Technology & Innovation 7 (2017) 203–218

Contents lists available at ScienceDirect

Environmental Technology & Innovation

journal homepage: www.elsevier.com/locate/eti

Technology options for faecal sludge management in developing countries: Benefits and revenue from reuse

Shubhra Singh [a,*], Riya Rachel Mohan [a], Sujaya Rathi [a], N. Janardhana Raju [b]

[a] *Center for Study of Science, Technology and Policy (CSTEP), No.18 &19, 10th Cross, Papanna Layout, Mayura Street, Nagashettyhalli, RMV II Stage, Bengaluru-560094, Karnataka, India*

[b] *School of Environmental sciences, Jawaharlal Nehru University, New Delhi-110067, India*

HIGHLIGHTS

- Raw faecal sludge causes environmental pollution and outburst of diseases.
- Technology options for faecal sludge management.
- The decision matrix prepared with respect to city constraint.
- IRR and payback period were used as financial indicators for treatment technologies.
- Treated faecal sludge has economic and environmental benefits.

ARTICLE INFO

Article history:
Received 26 August 2016
Available online 28 February 2017

Keywords:
Sanitation
Faecal sludge
Technology
Decision matrix
Benefits
Cost and revenue

ABSTRACT

This article provides technology options for the treatment of Faecal Sludge (FS) in developing countries to minimise exposure to FS and assesses its benefits along with possible revenue generation from reuse. FS that is collected from septic tanks poses management challenges in urban areas of developing countries. Currently, FS is dumped into the urban and peri-urban environment, posing great risks to the soil, surface water and groundwater quality. FS treatment technology usually consists of (1) primary treatment for the separation of the solid and liquid parts, and (2) sludge treatment, which is the final stage of treatment that is generated from the primary treatment. A decision matrix was prepared on the basis of primary and sludge treatment technological options with respect to land requirement, energy requirement, skill requirement, capital cost (CAPEX), operating cost (OPEX) and groundwater level. These parameters strongly influence the decision-making about the selection of the FS treatment technology. The selection of a FS treatment technology for a city also depends on the local conditions and priorities of the region with regard to sanitation such as population coverage, environmental and health benefits, elimination of open defecation, etc. Techno economic feasibility of different combinations of primary and sludge treatment technologies was conducted to evaluate its viability. The analysis was conducted across different classes of cities with varying population size. The combination of primary treatment technologies with solar sludge oven emerged to be the most economically viable options for FS treatments across different population size in developing countries.

---

* Corresponding author.
E-mail addresses: shubh.bhu@gmail.com (S. Singh), riyarachel@cstep.in (R.R. Mohan), sujaya@cstep.in (S. Rathi), rajunj7@gmail.com (N.J. Raju).

http://dx.doi.org/10.1016/j.eti.2017.02.004

Contents

---

1. Introduction

Sanitation refers to the maintenance of hygienic conditions by proper treatment and disposal of excreta. Excreta consists of urine and faeces which are not mixed with grey water. It has low volume but a high concentration of nutrients and pathogens. Inadequate sanitation can lead to the spread of diarrhoeal diseases (Lalander et al., 2013), whereas improved sanitation is known to have a significant positive impact on human health (Mara et al., 2010). At present, there is a lack of access to affordable sanitation facilities in developing countries. FS is the partially digested slurry or semisolid that is generated from the storage of excreta or black water, presence or absence of grey water (Strande et al., 2014). In urban areas of developing countries, about 53.1% of the households do not have a toilet/lavatory and about 38% of the urban households in India use septic tanks as onsite sanitation facility (Census of India, 2011). The faecal sludge collected from these systems is usually discarded directly into water bodies or nearby agricultural fields. This kind of a practice poses great risks to the soil, surface water and groundwater quality, in addition to contaminating the agricultural produce and causing the spread of fatal diseases such as diarrhoea, cholera and helminthiasis due to faecal contamination (Nguyen-Viet et al., 2009).

According to Castro-Rosas et al. (2012), 99% of faecal coliform, 85% of *Escherichia coli* and 7% of diarrheagenic *E. coli* are found in the ready-to-eat salad in Pachuca City, Mexico, where most of the locally consumed vegetables are irrigated with untreated sewage water. The World Health Organization (WHO) recommends that the level of faecal coliforms in wastewater that is used for irrigation should not exceed 1000 Colony-Forming Units (CFUs) or a Most Probable Number (MPN) of 100 ml (WHO, 2006). High levels of faecal coliform were recorded in the vegetables in the markets of Kumasi, Ghana, as they were contaminated by wastewater streams used for irrigation (Keraita et al., 2003).

In developing countries like India, poor nutritional status and poverty promote mortality and morbidity associated with excreta-related diseases. It is estimated that approximately 1.8 million children under the age of five die each year from diarrhoeal diseases worldwide, as reported by the WHO (2004), and 10% of the population in the developing world is severely infected with intestinal worms due to improper waste and excreta management (WHO, 2000). The estimated loss of about 62.5 million Disability-Adjusted Life Years (DALYs) or 4.3% of the overall global burden of disease is mainly attributed to diarrhoeal diseases alone. Unsafe water supply or scarcity of potable water, inappropriate sanitation and poor hygiene are the key factors responsible for about 88% of above estimated diseases (WHO, 2002). A higher risk of mortality has been observed in children with low weight (for their age) (WHO, 2000; Rice et al., 2000). The health impacts of wastewater and FS disposal are mainly due to specific pathogens, e.g., *Shigella* spp. (Esrey et al., 1991). Thus, exposure to excreta is an environmental and health hazard, and so minimising exposure in each and every part of the sanitation value chain becomes paramount. Similar to other developing nations, environmental sanitation condition in Ghana is also substantially lacking due to inadequate number of toilet facilities as well as insufficient waste disposal and treatment services.

Concentration of nutrients, pathogens, solid content, Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD) are excessively higher in FS. FS contains high amounts of excreted pathogens, which may induce plant and soil toxicity, and may have adverse effects on the metabolism of soil microorganisms. Once pathogens enter the environment, they can be transferred via either the mouth through eating infected vegetables or the skin (if schistosomes and hookworms) (Carr, 2001). Thus, proper excreta disposal and maintenance of optimal levels of personal and domestic hygiene are essential for protecting public health. In order to achieve the target of proper FS disposal, appropriate and ecologically sound technologies are essential which should not only economical, but also long lasting and prolonged for potential recovery of recyclable constituents from sludge since as explained above, FS are having very rich concentration of nutrients along with higher organic content. Faecal sludge management (FSM) helps to achieve the goal to transform cities into totally sanitised, healthy and liveable cities and towns. FS treatment technology described in this paper would in turn help in the implementation of policy in developing countries, such as the national urban sanitation policy (NUSP) in India, which aim to achieve cities free from open defecation. In India, the first faecal sludge treatment plant (FSTP) was recently constructed in Devanahalli in Karnataka. The FSTP is designed for 6 m^3 of septage, the treated sludge from which is used for manure production (CDD, 2016).

The key objective of the study is to assess existing FS treatment technologies that may be relevant for adoption in developing countries to minimise exposure to FS for urban sanitation improvements, and also to understand the benefits of sanitation with respect to cost recovery. This paper is divided into six sections. The second section of the paper discusses the constraints and reuse potential of FS in developing countries. The third section explains in brief the methodology, while fourth section explains the technology options for primary and sludge treatment. The fifth section describes the benefits and analyses the economic viability of technologies across different classes of cities.

2. Constraint and reuse potential of faecal sludge

2.1. Constraint of faecal sludge treatment in developing countries

Conversion of FS to valuable products without any foul odour, flies and pathogen transmission is a challenging task in developing countries. The choice of FS treatment methodology primarily depends on the sludge characteristics and their reuse option [e.g., land application, biogas production or landfilling (Kone et al., 2010)]. Sludge characteristics vary significantly depending on the location, water content and storage. For example, ammonium concentration in FS can vary from 300–3000 mg/L, while 60,000 Helminth Eggs (HE) can be present per litre of FS (Mang and Li, 2010). The FS characteristic determines the appropriate type of treatment and reuse. The wide variety of FS characteristics requires considering suitable options for primary treatment. Primary treatment is used for dewatering or solid–liquid separation or biochemical stabilisation of FS. Technologies for dewatering of FS have been reported previously (Pescod, 1971; Strauss et al., 1997, 1998). Dewatered sludge with low moisture content reduces transport loads and is easier to handle. Dewatering is also necessary prior to composting and landfilling to reduce the leachate percolation to the groundwater.

The choice of FS treatment methodology also depends on the practice used for FSM. In developing countries, households mostly use septic tanks, twin pits and manual emptying for FSM. The sludge collected from the septic tank and twin pit is biochemically more stable due to longer storage periods as the sludge is emptied from the septic tank and twin pits in 2–3 years. The sludge collected from frequent (regular or weekly) emptying is biochemically unstable and exhibits a high organic concentration.

The challenges that are explicitly faced by developing countries for treating FS are different from those faced while treating wastewater. The fact is that the organic and solid content as well as the pathogen concentrations are 10–100 times more impactful in FS than in municipal wastewater; therefore, suitable treatment is required for FS (Klingel et al., 2002). The choice of FS treatment option for a city should particularly depend on the local conditions and priorities of the region with regard to sanitation such as coverage, environmental and health benefits, elimination of open defecation, etc. Variation in population density, water usage and availability, soil type, level of water table, availability of capital, ability to pay and uncertainty about growth patterns strongly influence the decision-making about the selection of treatment.

2.2. Reuse potential of faecal sludge

Human excreta is a good source of organic matter and plant nutrients, which can be reused in agriculture as fertiliser and for soil amendment. Faeces in human excreta contains maximum of the organic matter whereas urine is having higher concentration of nitrogen (70%–80%) and potassium, however, even distribution of phosphorus is found in urine and faeces (Otterpohl et al., 2003). At the same time, excreta has a higher concentration of pathogenic microorganisms, and, therefore, requires adequate sanitisation prior to use (Albihn and Vinnerås, 2007; Winker et al., 2009). Some of the well-known techniques which cleanse and convert organic wastes into valued produce are: composting, vermicomposting, shallow trenches, anaerobic digester, solar drying, etc.

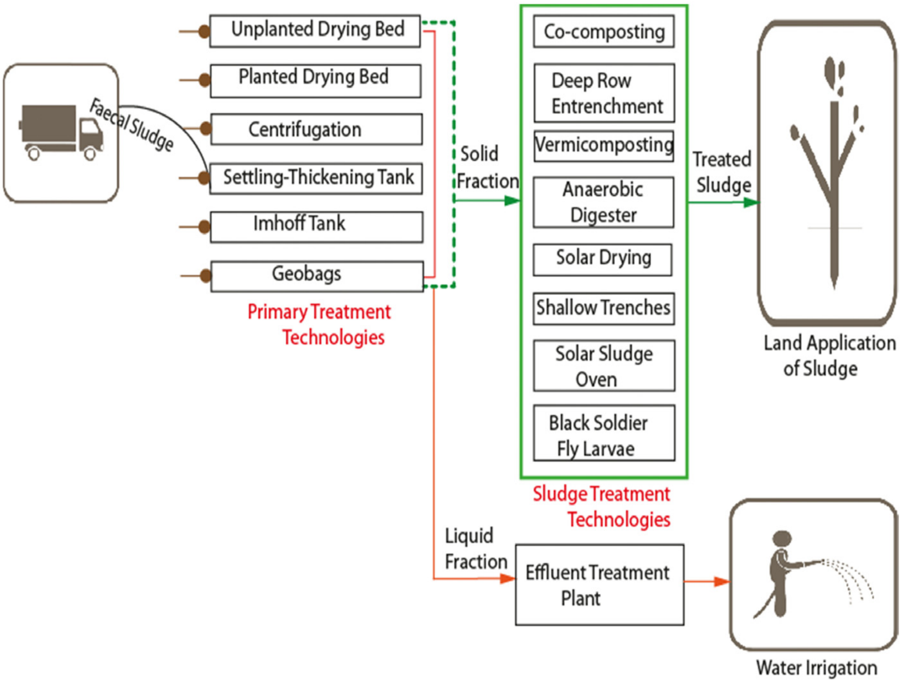

Fig. 1. Overview of technology options for faecal sludge treatment.

3. Methodology

Primary and sludge treatment technologies that are best suited for developing countries were identified through literature survey, books and through document analysis. General descriptions, advantages, constraints and a decision matrix for FSM technologies are provided in Section 4 for the reader to compare and contrast between the potential performance and scope of appropriate applications. Technically viable combinations of primary and sludge treatment technologies were chosen and assessed for their economic viability. Internal Rate of Return (IRR), which is the rate at which the net present value of all cash flows from a project or investment equals zero, was chosen as the economic indicator to measure the profitability of potential technology combinations. The net cash flow was calculated using the revenue generated from the reusable products and the annual operating expenses of the treatment systems. IRR was calculated for all chosen technology combinations for varying population sizes (i.e., 10,000–5 million) to study the economic viability of the technologies across different classes of cities. IRR of 10% were considered as the benchmark for the economic viability. Hence, FSM combinations providing an IRR greater than or equal to 10% were considered profitable. The payback period for the profitable combinations was calculated to understand the time required to recover the cost of an investment. The detailed economic analysis is provided in Section 5.2.

4. Faecal sludge management technologies

FS (which is discharged by collection and transport trucks) requires a preliminary screening before initiation of treatment, due to the high content of coarse waste such as rocks, sand, iron, wood, textiles and plastics, tissue and paper. In addition, the quality of FS collected from industrial and commercial areas should be tested to check for contamination (with metals, and/or high concentrations of oil, grease, fats, etc.).

FS treatment technologies usually comprise (1) primary treatment for the separation of the solid and liquid parts, and (2) sludge treatment, which is the final treatment that is generated from primary treatment. Treatment at very primary level results in reduction of sludge volume which in turn minimises the storage requirement as well as transportation costs, but it is an expensive high-tech solution. Age of FS and period of onsite storage affect the ability to dewater the sludge. Fresh sludge is more difficult to dewater than older sludge, which is more stabilised FS.

After treatment, three types of end products will be produced, i.e., screenings, treated sludge and liquid effluents. The liquid effluent generated from the primary treatment must be treated further to meet the requirements for water reuse or discharge into the environment. Low-cost technologies such as waste stabilisation ponds or wetlands could be used for the liquid treatment. Treatment technology options at the primary and sludge treatment level for FS are presented in Fig. 1. These treatment technologies are generally appropriate for the household level, ward level and city level. Each technology has different fields of application.

Table 1
Overview and removal efficiency of primary treatment options.

Treatment option	Design criteria	Removal efficiency	Preferred areas	Land requirement
Unplanted drying bed	100–200 kg TS/m^2/year (Kone et al., 2010)	SS: >95%, COD: 70%–90%, 100% HE (Cofie et al., 2006)	Peri-urban and rural areas.	0.05 m^2/capita for a 10-day cycle (TAC Report, 2013)
Planted drying bed	≤250 kg TS/m^2/Year, SAR: 20 cm/year	SS: 96%–99%, COD: 95%–98%, TS: 70%–80% (Kone et al., 2010)	Peri-urban and rural areas.	4000 m^2/MLD
Centrifugation		Solid recovery efficiency: 85%–98% (Nikiema et al., 2014)	Urban areas	–
Settling–thickening tank	SAR: 0.13 m^3/m^3 of raw FS HRT: ≥4 h	SS: 57%, COD: 24%, BOD: 12%, HE: 48% (Heinss and Strauss, 1999)	Peri-urban and rural areas.	0.006 m^2/capita (Kone et al., 2010)
Imhoff tank	–	SS: 50%–70%, BOD (30%–50%) (Barnes and Wilson, 1976)	Urban areas (suited for densely populated areas)	600 m^2/MLD
Geobag	–	–	Peri-urban and rural areas	–

TS, Total solid; SS, Suspended solid; COD, Chemical oxygen demand; HE, Helminth egg; SAR, Solid accumulation rate; BOD, Biological oxygen demand.

4.1. *Primary treatment (solid–liquid separation) technologies*

Primary treatment is used for solid–liquid separation (dewatering) as well as for treatment of the solid and liquid parts of FS that is generated from the septic tank. The technologies used for primary treatment are unplanted drying bed, planted drying bed, centrifugation, settling–thickening tank, Imhoff tank and geobag. Out of these technologies, centrifugation and geobag would be used only for solid–liquid separation, whereas unplanted drying bed, planted drying bed, settling–thickening tank and Imhoff tank would be used for solid–liquid separation as well as treatment of the solid and liquid parts. General overview and removal efficiency of primary treatment options are presented in Table 1.

4.1.1. *Unplanted drying bed*

Unplanted drying beds contain shallow filters filled with sand and gravel, with an under-drain at the bottom to collect the leachate. Approximately 50%–80% of the sludge volume is discharged as a leachate, which needs to be treated before being discharged into agricultural fields. After drying, the sludge is removed from the bed manually or mechanically and needs to be further treated by co-composting (Cofie et al., 2006). The sludge from an unplanted drying bed cannot be directly used for land application as a soil fertiliser due to the presence of pathogens.

The main advantages of unplanted drying bed are the low cost, good dewatering efficiency, no energy requirement, and the fact that they can be built and repaired with locally available materials. Constraints of this technology are the high land requirement, odours and flies, which are normally noticeable, labour-intensive removal, limited reduction of pathogens, and the need for further treatment of the liquid part.

4.1.2. *Planted drying bed*

A planted drying bed is sometimes called a vertical-flow constructed wetland, reed bed, planted dewatering bed or sludge bed with emergent plants. In Ouagadougou, emergent plants like *Andropogongayanus* and *Cymbopogonnardus*are used for the treatment of FS in planted drying beds (Joceline et al., 2016) Emergent plants are essential to improve the performance of planted drying beds for waste stabilisation and reduction of pathogens (Strauss et al., 1997).

The main advantages of a planted drying bed are that it is cost-effective, easy to operate, can handle high loading and has better sludge treatment than unplanted drying beds. The constraints of this technology are high land requirement, odours and flies, which are normally noticeable, labour-intensive removal of sludge, limited reduction of pathogens and the need for further treatment of the liquid part.

4.1.3. *Centrifugation*

Centrifugation is a type of mechanical dewatering that is mostly applied for the treatment of residual sludge in large-scale centralised wastewater treatment plants (Nikiema et al., 2014). This can be applied to thicken or dewater the sludge to different levels, by varying the operating conditions; however, it is difficult to operate a centrifuge (e.g., instant start-up and shut down are not possible as it may take an hour during which there is gradual increase/decrease in the speed of the centrifuge (Strande et al., 2014).

This technology requires lower land requirement, but needs skilled operators. The main constraints of this technology are higher power consumption, higher maintenance costs and fairly high noise levels.

4.1.4. Settling–thickening tank

A rectangular settling–thickening tank is used for FS treatment. The FS is discharged through a top inlet on one side and the supernatant exits through an outlet on the opposite side; solids settle at the bottom of the tank, whereas scum floats on the surface (Strande et al., 2014). An alternative for the treatment of FS could be to add the lime/ammonia directly into the settling–thickening tank. Lime stabilisation offers the advantages of precipitating metals and phosphorus, and reducing pathogens, odours, degradable organic matter, etc., from the wastewater sludge treatment (Mendez et al., 2002); it has been implemented in the Philippines for FS treatment (Pescon and Nelson, 2005). Ammonia treatment can also be applied for pathogen reduction.

It is a relatively robust and resilient technology, but with low reduction of pathogens. The end products of settling tanks cannot be discharged into water bodies or used directly in agriculture.

4.1.5. Imhoff tank

Imhoff tanks usually consist of a two-storey tank mechanism that utilises the force of gravity for the separation of solids from wastewater—a process known as primary sedimentation. The solid part that is generated from the Imhoff tank is degraded under anaerobic digestion within a lower chamber of the tank prior to sludge disposal (Crites and Technobanoglous, 1998).

The Imhoff tank treatment system requires a structure with depth. Depth may be a problem in the case of a high groundwater table. This treatment shows low reduction of pathogens, and so the effluent sludge and scum require further treatment. The main advantage of this technology is the low land requirement for construction and also the low cost for operation and maintenance.

4.1.6. Geobags

Geobags are used for dewatering of wet sludge (Kim et al., 2013). Before discharge of geobag sludge for land application, composting is required for the better quality of sludge. Dried sludge from geobags must be solar-dried to ensure pathogen/helminth eradication before composting. Permeable textiles are used to make geotube containers, which are used for sludge and sediment dewatering. This new and innovative technology is also economically viable with other alternative sludge-dewatering techniques (Dietvorst, 2012). This is a passive technique that does not need extensive and constant deployment of labour or frequent maintenance of equipment.

4.1.7. Decision matrix for primary treatment technology (solid–liquid separation)

Technologies for individual houses, communities or ward/city should be selected based on the user requirement and local conditions. The criteria for selection of appropriate technology depends on city constraint such as land requirement, energy requirement, level of groundwater table, capital and operating cost, skill requirement and reuse opportunity etc. Based on the constraint, a decision matrix was prepared for the primary treatment technologies options (Table 2). The decision matrix ascertains the favourability of a technology in comparison with other identified technologies. It shows that the unplanted drying bed, planted drying bed and geobags have high land requirements but low energy requirement. Imhoff tank requires a deep groundwater table for its operation. Treated waste generated from the centrifugation and geobag cannot be reused directly without further sludge treatment (Table 2).

4.2. Sludge treatment technologies

After dewatering of sludge, partially treated sludge is produced. This treated FS still contains pathogens and eggs of parasites, and cannot be directly used in agriculture. To improve the quality of sludge, further treatment is required. This is the final stage of treatment of sludge before discharge. The technologies used for further treatment of sludge are co-composting, deep row entrenchment, vermicomposting, anaerobic digester, solar drying, shallow trenches, solar sludge oven and black soldier fly larvae. Deep row entrenchment and shallow trenches can be considered as both a treatment and an end-use option.

4.2.1. Co-composting

This technology has been widely used for processing source-separated human faeces (WHO, 2006; Niwagaba et al., 2009). After dewatering of FS, the partially treated sludge is mixed with the organic fraction of municipal solid waste at a ratio of 1:2 or 1:3. The composting process needed well-balanced conditions of aeration and moisture for the survival of microbes. FS has high moisture and nutrient content, whereas municipal solid waste has good bulking properties and is rich in organic content. After composting, the resulting end product is stabilised organic matter that can be used as a fertiliser. The co-composting process takes 10–12 weeks and high temperature (50–70 °C) maintained for 3 weeks during co-composting for the destruction of helminth eggs and pathogenic bacteria. Thereafter, the temperature gradually decreases until the compost is matured.

The main advantages of co-composting are that pathogen reduction is high and a high removal of helminth eggs is possible (<1 viable egg/g TS). But this technology requires technical and managerial skills for operation and generation of safe products.

Table 2
Decision making matrix for primary treatment technology (solid–liquid separation) with respect to constraint.

Constraint	Legend		Unplanted drying bed	Planted drying bed	Centrifugation	Settling–thickening tank	Imhoff tank	Geobag
Land requirements	+ + +	High requirement						
	++	Medium requirement	+ + +	+ + +	+	+	+	+ + +
	+	Low requirement						
Energy required for daily operation	+ + +	High						
	++	Medium	+	+	++	+	+	+
	+	Low						
Shallow groundwater table	+ + +	Not favoured	++	++	++	++	+ + +	++
	++	Favoured						
CAPEX	+ + +	High cost						
	++	Medium cost	+	+	+ + +	+	++	++
	+	Low cost						
OPEX	+ + +	High cost	+	+	+ + +	+	++	++
	++	Medium cost						
	+	Low cost						
Skill requirement	+ + +	High						
	++	Medium	+	+	++	+	+ + +	+
	+	Low						
Reuse opportunity (reuse of the treated waste)	+ + +	High						
	++	Medium	++	++	+	++	++	+
	+	Low						

4.2.2. *Deep row entrenchment*

In the deep row entrenchment process, deep trenches are dug, which are then filled with sludge followed by covering with soil (Still et al., 2012). Earthmoving equipment is used in this technique to bury the sludge in plantation pits before planting takes place. The anaerobic conditions in the trench are accountable for reducing nitrification and, hence, restraining the leaching of nitrates. The entrenched sludge also acts as a form of slow-release fertiliser for trees. The organic matter and nutrients which are slowly released from the FS are beneficial for growth of trees that are planted on the top. The risk pathogen exposure of people gets reduced due to this. It also ensures adherence to the latest sludge guidelines for the disposal of non-faecal matter and for recycling of nutrients. Deep row entrenchment feasible for those areas where groundwater table is deep and sufficient land is available.

The benefits of this technology are CO_2 fixation and erosion protection through the plantation. Low groundwater table and high land requirement could be constraints.

4.2.3. *Vermicomposting*

Vermicomposting is a low-cost technology system using earthworms for composting faecal matter (Shalabi, 2006; Contreras-Ramos et al., 2005; Yadav et al., 2010). This technology is rapid, easily controllable, energy-efficient, cost-effective and produces zero waste for FSM (Eastman et al., 2001). After vermicomposting, two useful end products are produced, namely, earthworm biomass and vermicompost. Earthworms can consume practically all kinds of organic matter and can eat up to their own body weight in a day; e.g., 1 kg of earthworms can consume 1 kg of residues every day (Loh et al., 2005). C:N ratio determines the relative proportion of the mass of carbon to the mass of nitrogen in compost. The optimum C/N ratio for composting is considered to be 30%–35%, and microbial activity in this range is fast. A low C/N ratio can be further improved by adding common waste materials such as animal waste, bagasse or garden waste, etc. During vermicomposting, the moisture level should also be maintained at 50%–60% by periodic sprinkling of adequate quantity of tap (potable) water. Several epigeics (*Eisenia fetida, Eisenia andrei, Eudrilus eugeniae, Dendrobaena veneta, Perionyx excavatus* and *Perionyx sansibaricus*) have been identified for the degradation of organic waste materials for vermicomposting (Wong and Griffiths, 1991; Shalabi, 2006; Suthar, 2007).

The main advantages of this technology are easy operation, complete removal of pathogens and the end product, which is a good soil conditioner. However, technical and managerial skills are required for operating a vermicomposting plant.

4.2.4. Anaerobic digester

This technology is used for the digestion of organic matter in the presence of anaerobic microorganism. Biogas and slurry are produced during the treatment process (Salminen and Rintala, 2002). The amount of biogas produced from FS by anaerobic digestion depends on operating parameters such as stability of the sludge, the COD of the sludge and temperature (Bensah et al., 2010; Song et al., 2012; Dahunsi and Oranusi, 2013). The quality of FS needs to be checked before anaerobic digestion, as FS or partially digested sludge has a low concentration of biodegradable organics. In this case, the low content of biodegradable organics would result in a low volume of biogas but high solid accumulation, resulting in significant operational costs with limited benefits. Digested FS may not be suitable for anaerobic digestion, depending on the level of stabilisation it has undergone. However, expert design along with skilled labour is required for construction of an anaerobic digester.

4.2.5. Solar drying

Solar drying treatment is generally done in greenhouse structures with glassy covers, concrete basins and walls (Bennamoun, 2012). Sludge is disposed into the concrete basins and processed for about 10–20 days. An option for batch or continuous operation is available with devices for controlling the greenhouses conditions (e.g., ventilation, air mixing, temperature). Solar variation, air temperature and ventilation rate are the main factors influencing the evaporation efficiency in these systems, with the air mixing and the initial dry solid content of the sludge impacting the operation (Seginer and Bux, 2005). The sludge moisture content decreases from 85% to 6% in 7–12 days in summer conditions, but may require up to 32 days in autumn conditions (Mathioudakis et al., 2009). Solar drying has low energy requirements and investment costs technology for FSM. The main constraints of this technology are the space requirement and the need for a mechanical means to turn the sludge, as well as to ventilate the greenhouses.

4.2.6. Shallow trenches

It is a simple system that helps in land remediation, and causes no nuisance to neighbours in terms of smell or aesthetic flexibility. A shallow trench can be used irrespective of the quality and quantity of sludge. Shallow trench technique is safe for groundwater and that the sludge is beneficial to the growth of trees (WASHplus Project, 2011). However, the main constraints of this technology are the space requirement.

4.2.7. Solar Sludge Oven

Solar Sludge Oven is an insulated box covered with glass that sits at a 45° angle. When exposed to sunlight, the temperature inside the box increases. The temperature inside a well-insulated box can reach up to 180 °C. As part of sludge treatment, bricks and cement are used to build sludge ovens with a capacity of 6 m^3 individually on the disposal site in Ambositra (WASHplus Project, 2011). Removable transparent roofing sheets are used to cover the half-buried and insulated oven. The oven is closed once full due to loading of sludge into it. As the temperature of the oven rises, depending on the degree of insulation, the drying process in the sludge continues over several months until the pits are emptied again. As a result, the dry residual sludge becomes hygienic and can be buried under a thin layer of soil or can be utilised as a conditioner for the improvement of soil fertility in neighbouring orchards. This technology is very simple to use and the sludge generated from this technology is very hygienic, but the processing capacity is limited (only ≈ 12 m^3 per 8 months) and the cost is higher compared with burial pits or trenches, which could be considered a constraint.

4.2.8. Black soldier fly larvae (BSFL)

BSFL feed on decomposing organic matter such as human and animal manure, as well as fruit and vegetable waste (Tomberlin et al., 2002). It is found in tropical regions and is an excellent protein source in animal feed. The feeding activity of BSFL decreases the dry mass of waste significantly. The insect protein could be used in animal feed to replace fishmeal. The global price for fishmeal has tripled from 2005 to 2013, and is expected to remain high due to declining wild fish stocks and the ongoing increase of aquaculture, the revenue potential from these larvae is very attractive (Naylor et al., 2009). However, BSFL treatment is not an adequate sanitisation method for FS intended for agricultural reuse in areas with prevalence of ascariasis. Further treatment is required if the product is to be used as fertiliser for food crops. Ammonia sanitisation is an affordable and reliable treatment which produces not only a sanitary product, but also a product with increased nutrient content (Vinnerås, 2007; Lalander et al., 2013).

4.2.9. Decision matrix for sludge treatment technology

A decision matrix was prepared with respect to constraint for the sludge treatment technologies options (Table 3). The matrix shows that deep row entrenchment and shallow trenches are low-cost options with respect to CAPEX and OPEX but low reuse opportunity. Co-composting, vermicomposting, anaerobic digester, solar drying, shallow trenches, solar sludge oven and BSFL do not depend on the groundwater level for operation, whereas deep row entrenchment requires groundwater located deep (Table 3). Treated waste generated from the co-composting, vermicomposting, anaerobic digester, solar drying, solar sludge oven and BSFL has reuse opportunity which would generate revenue to financially sustain the system.

Table 3
Decision making matrix for sludge treatment technology with respect to constraint.

Constraint	Legend		Co-composting	Deep row entrenchment	Vermicomposting	Anaerobic digester	Solar drying	Shallow trenches	Solar sludge oven	BSFL
Land requirements	+++	High requirement								
	++	Medium requirement	+++	+++	+++	+	+++	+++	+	+++
	+	Low requirement								
Energy required for daily operation	+++	High								
	++	Medium	+	+	+	+	+	+	+	+
	+	Low								
Shallow groundwater table	+++	Not favoured	++	+++	++	++	++	++	++	++
	++	favoured								
CAPEX	+++	High cost								
	++	Medium cost	+++	+	+++	+++	++	+	++	+++
	+	Low cost								
OPEX	+++	High cost								
	++	Medium cost	+++	+	+++	+++	++	+	+	+++
	+	Low cost								
Skill requirement	+++	High								
	++	Medium	+	+	++	+++	++	+	++	++
	+	Low								
Reuse opportunity	+++	High								
	++	Medium	+++	+	+++	++	+++	+	+++	+++
	+	Low								

5. Cost–benefit analysis of FSM technologies

The organic matter and other nutrients in the FS can be recovered and reused as a soil conditioner, biogas, biochar, etc. These products can be sold in the market and the revenue generated from it can recover the capital and operating costs of FSM technologies. The techno economic feasibility of different combinations of primary and sludge treatment technologies has been conducted to check its business viability.

5.1. Benefits of treated sludge

FS that has undergone some degree of treatment and is no longer raw is called "treated sludge". Treated sludge, which is fully stabilised sludge, can be used for different purposes such as combustion as fuel (Werther and Ogada, 1999; Muspratt et al., 2014; Strande et al., 2014), char production (Rulkens, 2008), in building materials (Jordan et al., 2005; Lin et al., 2012) and as a soil conditioner (Nikiema et al., 2013; Diener et al., 2014). Use of treated or raw sludge as a soil conditioner and fertiliser is very popular. Generally in developing countries, farmers use wastewater, raw or treated sludge for irrigation and soil conditioning to minimise the purchase of chemical fertiliser. FS contains a lower concentration of heavy metals than artificial manure, and can be considered a clean fertiliser. Since FS contains pathogens, the treatment of the faecal matter is necessary before it can be utilised as a fertiliser. Farmers of Dakar use, on average, 246 m^3 of FS per year as a soil conditioner. In Ghana, co-composting from FS has previously shown limited demand by farmers, but nitrogen enrichment is suggested to increase value and demand (Nikiema et al., 2013). The average price is US$4/tonne for FS that is generated from drying beds, in contrast to animal manure, which sells at twice as much due to its higher acceptance (Diener et al., 2014). In Dakar, horticulturists and farmers mix the FS with *Casuarina equisetifolia* L. leaves (Filao leaves) and animal manure to achieve a consistency that is easier to work with, as the form in which the FS is currently sold is not considered optimal (Diener et al., 2014). Local farmers can be convinced for using human excreta in their fields if the sludge could be properly dried by using appropriate techniques.

Table 4
Technical and financial parameters for each primary technology.

Primary technology	Yield (%)	CAPEX (US$/KLD)	OPEX (US$/KLD)
Unplanted drying bed	35%[a]	445	13.34[b]
Planted drying bed	30%[b]	474	14.22[b]
Centrifugation	92%[b]	25,166	9764[e]
Settling–thickening tank	95%[c]	799[f]	0.06[f]
Imhoff tank	50%[d]	741	44.45
Geobags	12.5%	1226[f]	244.37[f]

[a] Tilley et al. (2014).
[b] Nikiema et al. (2014).
[c] Strauss and Montangero (2002).
[d] Ajibade (1999).
[e] Solids Handling Plan (2010).
[f] Sharrer et al. (2010).

Table 5
Technical and financial parameters for each sludge treatment technology.

Sludge treatment technologies	Yield (%)	CAPEX (US$/m^3)	OPEX (US$/m^3)
Co-composting	25%[a]	5458[c]	775[c]
Deep row entrenchment	–	2.25	0.00[a]
Vermicomposting	25%[a]	6549[c]	930[c]
Solar drying	31.6%[b]	877.55[b]	50.87[b]
Shallow trenches	–	2.25[d]	0.00
Solar sludge oven	32%	95.8[d]	0.96[e]

[a] AIT Tool (2016).
[b] Chavez (2013).
[c] IL & FS Ecosmart Limited, M/s Organophos (2009).
[d] WASHplus Project (2011).
[e] Kurt et al. (2015).

5.2. *Techno-economic assessment of FSM technologies*

Treated sludge is more hygienic in nature and has an improved structure, so it has more market value. The practical implementation of any technology depends on its techno-economic viability. Usage of thickening and dewatering technologies produces denser sludge with approximately 32% dry solid concentration, while drying technologies produce sludge with more than 62% dry solid concentration (Flaga, 2005). As shown in Tables 4 and 5, the solid retention for the thickening and dewatering technologies like centrifuge and settling–thickening tank is more than 90%, and, hence, these can generate more revenue. Sludge for use in agricultural purposes is always preferred to have a solid concentration of more than 60%. Hence, an appropriate combination of dewatering and drying technology could generate better revenue. A detailed financial model was prepared to conduct a cost–benefit analysis for different combinations of primary treatment and sludge treatment components. The financial assessment was performed for a 10-year-long period. Sludge treatment technologies like anaerobic digester and BSFL to produce biogas and animal protein, respectively are still being tested with FS at a laboratory or pilot scale. Since this technology has not yet been implemented at the field, BSFL is not considered for this assessment. In case of biogas digester, since the feed used is long-term digested FS from septic tanks, the economic assessment of biogas generation is not considered (Diener et al., 2014).

There are basically two important parameters that affect the financial viability of a treatment plant—yield factor and population served.

Yield factor: Yield is the quantity of organic solids that will be retained after the treatment process. The yield factor from each technology directly affects the quantity of manure produced, which in turn affects the revenue generated. The yield factor from the sludge treatment technologies is between 25% and 32%. Shallow trenches and deep row entrenchments are planted burying pits, and, hence, no revenue can be generated by selling the manure produced inside the pit. These technologies generate a social cost–benefit that is not included in the current analysis.

Population served: With the population changing in each city, the viability of treatment options also changes. Table 6 shows the categorisation of Indian cities.

A detailed financial analysis was conducted to calculate the IRR and payback period using the revenue and overall operating expense of the project. The revenue generated from the final product was calculated based on the quality and quantity of the manure. The quality of manure generated from co-composting and vermicomposting is higher as compared to other sludge treatment techniques. Hence, the price of compost or vermicompost was taken to be US$ 104/tonne (Mukherjee, 2015), whereas the price of the manure generated from the other sludge treatment technologies was taken to be US$ 74/tonne. Quantity of manure was calculated using the combined yield factor of primary and sludge treatment technology. Combined yield factor is calculated by multiplying the yield factors of primary and sludge treatment technologies. The overall operating expense of these treatment technologies was calculated from the OPEX values provided in Tables 4 and 5. On

Table 6
Categorisation of cities.

Class	Population
IA	Over 5.0 million
IB	1.0–5.0 million
IC	0.1–1.0 million
II	50,000–99,999
III	20,000–49,999
IV	10,000–19,999
V	5000–9999
VI	Less than 5000

Table 7
Assumptions used in the financial model.

Parameters	Value
Inlet total solids	22,000 mg/L
Density of FS	1125.5 kg/m^3
FS generation	250 g/day/capita
Escalation rate on the price of compost and manure	5% per annum
Escalation rate on treatment plant operating cost	2% per annum
Salvage value	5%

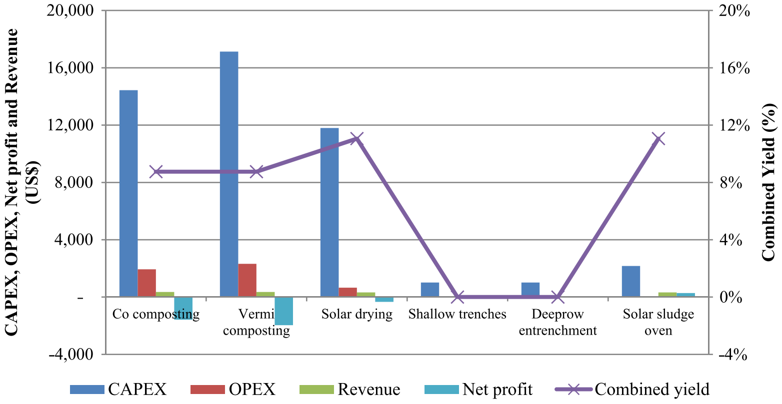

Fig. 2. Variation in financial parameters generated from an unplanted drying bed with the six sludge treatment options.

considering the inflation rate and time value of money, a yearly escalation rate on the price of manure and operating cost of treatment plant was considered. Table 7 shows the basic assumptions used for performing the cost–benefit analysis. The net cash flow of each treatment technology combination was calculated based on the difference between revenue and expense. A salvage value of 5% was considered at the end of the lifetime of the project.

The six primary technologies were technically compatible with the six sludge treatment options shown in Tables 4 and 5. Hence, thirty-six combinations of treatment technologies were generated and their financial analysis was performed to understand their cost-effectiveness. In order to understand the change in CAPEX, OPEX and revenue generated from combinations of primary treatment technology and sludge treatment technologies, the cheapest technology, unplanted drying bed, was chosen as the primary treatment technology and combined with the six sludge treatment options as shown in Fig. 2. The primary vertical axis shows the CAPEX, OPEX and revenue generated from the combination while the secondary vertical axis shows the combined yield from the treatment combinations (Fig. 2). Combination of unplanted drying bed with solar sludge oven generates the highest net profit among the six combinations. Though solar drying and solar sludge oven provides same yield, solar sludge oven requires lesser CAPEX for implementation. Co-composting, vermicomposting and solar drying are costlier and generate low yield as compared with the other sludge treatment options.

To understand the effect of population size on the viability of the treatment plant, the model was run for population sizes based on the classification of Indian cities. The quality of sludge was considered to be the same for all classes of the cities. A baseline case with the price of the compost/vermicompost and manure generated from other sludge treatment technologies were taken as US$ 104/tonne and US$ 74/tonne, respectively. IRR was calculated for all technology combinations at varying population sizes.

The price of compost was found to vary from US$ 0.074 to 2/kg, across several online shopping websites (Amazon, 2016). The average price of the compost is US$ 1040/tonne. In order to incorporate the varying market price, a scenario analysis was

Table 8
Technology combinations generating positive IRR (Baseline case).

Population size	Sludge treatment technology	Primary treatment technology					
		Unplanted drying bed	Planted drying bed	Centrifugation	Settling–thickening tank	Imhoff tank	Geobags
10,000	Solar sludge oven	10%	8%	–	16%	6%	–
20,000	Solar sludge oven	17%	15%	–	21%	14%	–
50,000	Solar sludge oven	23%	22%	–	25%	22%	–
1,00,000	Solar sludge oven	25%	25%	–	26%	25%	3%
10,00,000	Solar sludge oven	28%	28%	16%	28%	28%	25%
50,00,000	Solar sludge oven	28%	28%	25%	28%	28%	27%

Table 9
Technology combinations generating positive IRR (Scenario analysis).

Population size	Sludge treatment technology	Primary treatment technology					
		Unplanted drying bed	Planted drying bed	Centrifugation	Settling–thickening tank	Imhoff tank	Geobags
10,000	Co-composting	9%	9%	–	10%	9%	–
	Vermicomposting	3%	3%	–	4%	3%	–
	Solar drying	23%	22%	–	24%	22%	–
	Solar sludge oven	153%	138%	–	181%	141%	21%
20,000	Co-composting	10%	10%	–	11%	10%	–
	Vermicomposting	4%	4%	–	4%	3%	–
	Solar drying	24%	24%	–	25%	24%	11%
	Solar sludge oven	197%	184%	–	220%	187%	54%
50,000	Co-composting	11%	11%	–	11%	11%	6%
	Vermicomposting	4%	4%	–	4%	4%	0.01%
	Solar drying	25%	25%	1%	25%	25%	19%
	Solar sludge oven	239%	231%	33%	252%	233%	114%
1,00,000	Co-composting	11%	11%	0.4%	11%	11%	9%
	Vermicomposting	4%	4%	–	4%	4%	2%
	Solar drying	25%	25%	13%	26%	25%	22%
	Solar sludge oven	258%	253%	78%	265%	254%	164%
10,00,000	Co-composting	11%	11%	10%	11%	11%	11%
	Vermicomposting	4%	4%	3%	4%	4%	4%
	Solar drying	26%	26%	24%	26%	26%	25%
	Solar sludge oven	277%	276%	231%	278%	276%	261%
50,00,000	Co-composting	11%	11%	11%	11%	11%	11%
	Vermicomposting	4%	4%	4%	4%	4%	4%
	Solar drying	26%	26%	25%	26%	26%	26%
	Solar sludge oven	279%	278%	268%	279%	279%	275%

conducted by increasing the price of compost and other manure by 10 times from the baseline. The economic feasibilities of the treatment technologies were further checked.

The baseline case (price of compost/vermicompost and other manure as US$ 104/tonne and US$ 74/tonne, respectively) and scenario case (price of compost/vermicompost and other manure as US$ 1040/tonne and US$ 740/tonne, respectively) study generated 29 and 128 technology combinations, respectively providing a positive IRR. The combinations generating positive IRR are shown in Tables 8 and 9. In small cities, costly technology like centrifugation is not a viable option as the sludge generated from these cities is small. However, as the population size increases across the cities, more efficient and costly technologies will become viable with higher generation of revenue.

Technologies generating an IRR of more than 10% were considered as economically feasible. The baseline case generated 26 economically feasible options. Solar sludge oven was the only financially viable sludge treatment options in this case. The project IRR varied from 10% to 16% for a population size of 10,000 and went up to 28% for a population size of 5 million. Table 10 shows the various techno-economically feasible options against various population sizes.

With the increase in price of the compost and manure, scenario analysis generated 91 economically feasible options. The financially viable sludge treatment options in scenario analysis are co-composting, lime stabilisation, solar drying and solar sludge oven. The project IRR varied from 10% to 181% for a population size of 10,000 and went up to 279% for a population size of 5 million. Table 11 shows the various techno-economically feasible options against various population sizes for the scenario analysis.

From the baseline case and scenario analysis, it can be seen that the solar sludge oven option is the most feasible sludge treatment options across all population size. In the baseline case, it generates an IRR between 3% and 28% based on various

Table 10
Techno-economically feasible options in baseline case.

Primary treatment technology	Population size					
	10,000	20,000	50,000	1,00,000	10,00,000	50,00,000
Unplanted drying bed	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven
Planted drying bed		Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven
Centrifugation				Solar sludge oven	Solar sludge oven	Solar sludge oven
Settling–thickening tank	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven
Imhoff tank		Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven
Geobags				Solar sludge oven	Solar sludge oven	Solar sludge oven

Table 11
Techno-economically feasible options in scenario analysis.

Primary treatment technology	Population size					
	10,000	20,000	50,000	1,00,000	10,00,000	50,00,000
Unplanted drying bed	Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven
Planted drying bed	Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven
Centrifugation			Solar sludge oven	Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven
Settling–thickening tank	Co-composting Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven
Imhoff tank	Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven
Geobags	Solar sludge oven	Solar drying Solar sludge oven	Solar drying Solar sludge oven	Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven	Co-composting Solar drying Solar sludge oven

population sizes. As the population size increases, the choices of economically viable technology combinations increased in baseline case and scenario analysis 1. In the baseline case, solar sludge oven became a feasible option for population sizes above 10,00,000 for all the six primary treatment technologies. Similarly, co-composting, solar drying and solar sludge oven became the feasible option in case of scenario analysis. Centrifugation, a thickening and dewatering technology, was not economically feasible with any of the sludge treatment technologies till population size increased to 50,000 and 10,00,000 in case of scenario analysis and baseline case. Hence, Class-IA and IB cities will have better options for economically viable FS treatment methods.

Similarly, the payback period of treatment plants using a solar sludge oven is low as compared with that of other technologies. Figs. 3 and 4 show a reducing trend of the payback period with increase in population size. At lower population

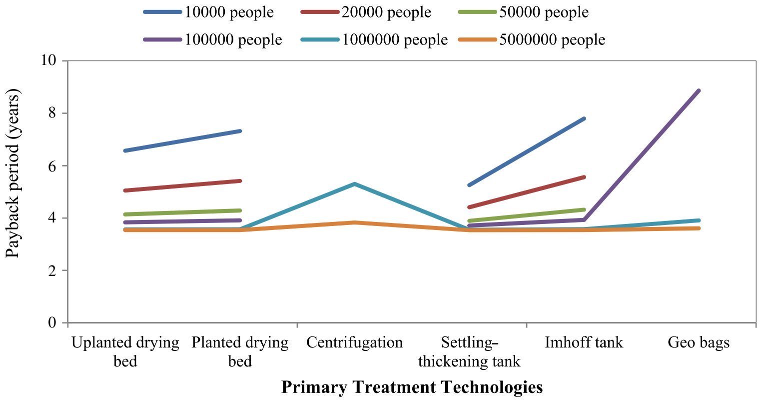

Fig. 3. Payback period for combinations of primary technologies with the solar sludge oven technology (baseline case).

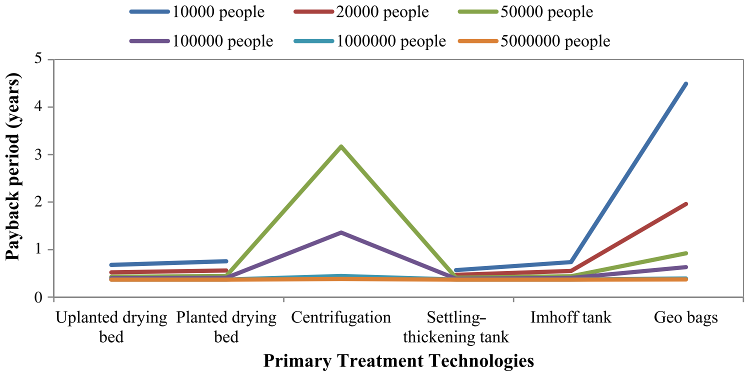

Fig. 4. Payback period for combinations of primary technologies with the solar sludge oven technology (Scenario analysis).

size, the payback period for centrifugation and geobags cannot be calculated due to the highly negative profit incurred from them.

The maximum payback period calculated in the baseline case and scenario analysis was 8.86 and 4.49 years, respectively. In the baseline case, the maximum time required for cost recovery was for the combination of solar sludge oven with geobags (8.86 years), whereas minimum time was required with settling–thickening tank (3.53 years). The payback period of each of the six primary treatment technologies was less than 4 years while designing for a population size of more than 5 million. In scenario analysis, the payback period reduced to less than 0.5 years for a population size of greater than 1 million.

5.3. *Limitations of the study*

This study has the following limitations:

- It has focused only on the FS treatment technology and has not considered effluent treatment technologies.
- The capital cost, operating costs and yield of the primary and sludge treatment technologies are based on literature review and not specific to the developing nations. The costs are not based on a consistent year, and, hence, the inflation rates are not considered in the calculation.
- Costs of unplanted drying beds, planted drying beds, vermicomposting and deep row entrenchments are based on expert opinions in the relevant sector. Similarly, the yield factors of geobags, co-composting are obtained from experts.
- The final revenue from the treatment is considered with the assumptions that the users are willing to pay for the manure. The price of the manure from various sludge treatment technologies were obtained from experts.

6. Conclusion

Rapid urbanisation and population growth generates enormous quantities of FS. Generally in developing countries, households use septic tanks for storage and treatment of excreta. FS waste is generated from septic tanks; it causes environmental pollution and outburst of diseases. This FS could, alternatively, be utilised as a raw material for useful produces, which can help in protecting our fragile environment and human resources by controlling the spread of excreta-related diseases. Primary and sludge treatment technology is required to produce the better quality of sludge. The treatment technologies should be selected based on the user requirement and local conditions of the ward or city. A decision matrix was prepared for the primary and sludge treatment option with respect to constraints which shows that the unplanted drying bed, planted drying bed, geobags, co-composting, vermicomposting and BSFL technology have high land requirements but do not need energy. The FS treatment technologies would help in the implementation of sanitation policies that aim to achieve cities free from open defecation. Technologies applied for FSM generate valuable and beneficial FS end products, which will help the slum dwellers to appropriately manage their own FS and also generate revenue for employment and business. A cost–benefit analysis of different combinations of primary and sludge treatment technologies was performed for different classes (based on population size) of Indian cities. Solar sludge oven is the most techno-economically feasible sludge treatment option in terms of cost and yield which can be used with a primary treatment, across all population size. The primary treatment technologies such as centrifugation and geobags is suitable for higher population sizes like Class IA and IB cities, whereas the other technologies like planted drying bed, unplanted drying bed, settling–thickening tank and Imhoff tank are viable for the all population sizes. The revenue from the sale of manure was assumed as US$ 104/tonne in the financial analysis. This generated a low IRR for many treatment technology combinations. The manure produced from FS has a higher organic content and has to be sold at a higher price as compared to manure generated from solid waste management plant. Using FS as a valuable product could help to address both the sanitation challenge as well as offer environmental benefits in terms of organic fertiliser.

Acknowledgement

The authors are thankful to the Bill and Melinda Gates Foundation (Grant No. 2013/07/OPP1087912) for their support.

References

AIT Tool, 2016. Financial and Technical assessment Tool. FSMToolbox. http://fsmtoolbox.com/main/tools.

Ajibade, F. 1999. Waste water Treatment. https://www.scribd.com/doc/192016672/Wastewater-Treatment.

Albihn, A., Vinnerås, B., 2007. Biosecurity and arable use of manure and biowaste—treatment alternatives. Livestock Sci. 112 (3), 232–239. http://dx.doi.org/10.1016/j.livsci.2007.09.015.

Amazon, 2016. http://www.amazon.in/s/ref=nb_sb_noss_1?url=node%3D3638818031&field-keywords=compost.

Barnes, D., Wilson, F., 1976. The Design and Operation of Small Sewage Works. John Wiley & Sons, Inc., New York.

Bennamoun, L., 2012. Solar drying of wastewater sludge: A review. Renew. Sustain. Energy Rev. 16 (1), 1061–1073.

Bensah, E., Antwi, E., Ahiekpor, J., 2010. Improving sanitation in Ghana—role of sanitary biogas plants. J. Eng. Appl. Sci. 5 (2), 125–133.

Carr, R., 2001. Excreta-related infections and the role of sanitation in the control of transmission. In: World Health Organization, Water Quality: Guidelines. Standards and Health, London.

Castro-Rosas, J., Cerna-Cortés, J.F., Méndez-Reyes, E., Lopez-Hernandez, D., Gómez-Aldapa, C.A., Estrada-Garcia, T., 2012. Presence of faecal coliforms, *Escherichia coli* and diarrheagenic *E. coli* pathotypes in ready-to-eat salads, from an area where crops are irrigated with untreated sewage water. Int. J. Food Microbiol. 156 (2), 176–180.

CDD, 2016. Faecal Sludge Treatment Plant, Devanahalli, Bangalore, http://www.cddindia.org/downloads/e-Disha/P-e-Disha-June-2016.pdf.

Census of India, 2011. Houses, Household Amenities and Assets; House-listing and Housing Census Data Highlights—2011.

Chavez, M.E. 2013. Solar Sludge Drying in the WWTP of Managua - Nicaragua. https://www.kfwentwicklungsbank.de/PDF/Entwicklungsfinanzierung/Sektoren/Wasser/Veranstaltungen/04_02_Mendoza_Pr%C3%A4sentation_Infrastructure_Conference.pdf.

Cofie, O.O., Agbottah, S., Strauss, M., Esseku, H., Montangero, A., Awuah, E., Kone, D., 2006. Solid–liquid separation of faecal sludge using drying beds in Ghana: Implications for nutrient recycling in urban agriculture. Water Res. 40 (1), 75–82. http://dx.doi.org/10.1016/j.watres.2005.10.023.

Contreras-Ramos, S.M., Escamilla-Silva, E.M., Dendooven, L., 2005. Vermicomposting of biosolids with cow manure and oat straw. Biol. Fertility Soils 41 (3), 190–198. http://dx.doi.org/10.1007/s00374-004-0821-8.

Crites, R., Technobanoglous, G., 1998. Small and Decentralized Wastewater Management Systems. McGraw-Hill, http://bases.bireme.br/cgi-bin/wxislind.exe/iah/online/?IsisScript=iah/iah.xis&src=google&base=REPIDISCA&lang=p&nextAction=lnk&exprSearch=93273&indexSearch=ID.

Dahunsi, S.O., Oranusi, U.S., 2013. Co-digestion of food waste and human excreta for biogas production. British Biotechnology Journal 3 (4), 485–499.

Dietvorst, 2012. Fecal Sludge Management: A smelly but fruitful business! Sanitation Updates. https://sanitationupdates.wordpress.com/2012/10/26/fecal-sludge-management-a-smelly-but-fruitful-business.

Diener, S., Semiyaga, S., Niwagaba, C., Muspratt, A., Gning, J., Mbéguéré, M., Ennin, J., Zurbrugg, C., Strande, L., 2014. A value proposition: Resource recovery from faecal sludge-Can it be the driver for improved sanitation? Resources. Resour. Conserv. Recy. 88, 32–38. http://dx.doi.org/10.1016/j.resconrec.2014.04.005.

Eastman, B.R., Kane, P.N., Edwards, C.A., Trytek, L., Gunadi, B., Stermer, A.L., Mobley, J.R., 2001. The effectiveness of vermiculture in human pathogen reduction for USEPA biosolids stabilization. Compost Sci. Utilization 9 (1), 38–49. http://dx.doi.org/10.1080/1065657X.2001.10702015.

Esrey, S., Potash, J., Roberts, L., Shiff, C., 1991. Effects of improved water supply and sanitation on ascariasis, diarrhoea, dracunculiasis, hookworm infection, schistosomiasis, and trachoma. Bull. World Health Organ. 69 (5), 609–621.

Flaga, A., 2005. Sludge Drying. Institute of Heat Engineering and Air Protection. Cracow University of Technology, ul. Warszawska, Kraków, Poland, http://rymd.lwr.kth.se/Forskningsprojekt/Polishproject/rep13/Flagasludgedrying73.pdf.

Heinss, U., Strauss, M. 1999. Co-treatment of faecal sludge and wastewater in tropical climates. SOS—Management of sludges from on-site sanitation. EAWAG/SANDEC.

IL & FS Ecosmart Limited, M/s Organophos, 2009. CDM: Establishment of Compost Production Unit of 100 TPD at Lalganj. https://cdm.unfccc.int/Projects/DB/RWTUV1239794223.57/view.

Joceline, S.B., Koné, M., Yacouba, O., Arsène, Y.H., 2016. Planted sludge drying beds in treatment of faecal sludge from ouagadougou: Case of two local plant species. J. Water Res. Protect. 8 (7), 697–705. http://dx.doi.org/10.4236/jwarp.2016.87057.

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

Keraita, B., Drechsel, P., Amoah, P., 2003. Influence of urban wastewater on stream water quality and agriculture in and around Kumasi, Ghana. Environ. Urban. 15 (2), 171–178. http://dx.doi.org/10.1177/095624780301500207.

Kim, H., Jamin, J., Won, M., Sung, H., Lee, J. 2013. A study on the behaviour of dredged soil stratified in a transparent geobag, in: The 2013 World Congress on Adv. Struct. Eng. Mech., ASEM13, jeju, Korea: pp. 2980–2987.

Klingel, F., Montangero, A., Kone, D., Strauss, M., 2002. Fecal sludge management in developing countries, a planning manual. In: EAWAG: Swiss Federal Institute for Environmental Science and Technology Sandec: Department for Water and Sanitation in Developing Countries.

Kone, D., Cofie, O.O., Nelson, K., 2010. Low-cost Options for Pathogen Reduction and Nutrient Recovery from Faecal Sludge. International Water Management Institute, https://ideas.repec.org/p/iwt/bosers/h042609.html.

Kurt, M., Aksoy, A., Sanin, F.D., 2015. Evaluation of solar sludge drying alternatives by costs and area requirements. Water Res. 82, 47–57. http://dx.doi.org/10.1016/j.watres.2015.04.043.

Lalander, C., Diener, S., Magri, M.E., Zurbrügg, C., Lindström, A., Vinnerås, B., 2013. Faecal sludge management with the larvae of the black soldier fly (*Hermetia illucens*)- From a hygiene aspect. Sci. Total Environ. 458–460, 312–318. http://dx.doi.org/10.1016/j.scitotenv.2013.04.033.

Lin, Y., Zhou, S., Li, F., Lin, Y., 2012. Utilization of municipal sewage sludge as additives for the production of ecocement. J. Hazard. Mater. 213–214, 457–465. http://dx.doi.org/10.1016/j.jhazmat.2012.02.020.

Loh, T.C., Lee, Y.C., Liang, J.B., Tan, D., 2005. Vermicomposting of cattle and goat manures by *Eisenia fetida* and their growth and reproduction performance. Biores. Technol. 96, 111–114. http://dx.doi.org/10.1016/j.biortech.2003.03.001.

Mang, H., Li, Z. 2010. Technology review of biogas sanitation. Deutsche gesellschaft für internationale zusammenarbeit. http://www.susana.org/en/resources/library/details/877.

Mara, D., Lane, J., Scott, B., Trouba, D., 2010. Sanitation and health. PLoS Med. 7 (11), http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2981586/.

Mathioudakis, V.L., Kapagiannidis, A.G., Athanasoulia, E., Diamantis, VI, Melidis, P, Aivasidis, A., 2009. Extended dewatering of sewage sludge in solar drying plants. Desalination 248 (1), 733–739.

Mendez, J., Jimenez, B., Barrios, J., 2002. Improved alkaline stabilization of municipal wastewater sludge. Water Sci. Tech. 46, 139–146.

Mukherjee, S. 2015. Centre sniffs out policy for manure from city waste. http://www.business-standard.com/article/economy-policy/centre-sniffs-out-policy-for-manure-from-city-waste-115070900021_1.html.

Muspratt, A.M., Nakato, T., Niwagaba, C., Dione, H., Kang, J., Stupin, L., Regulinski, J., Mbéguéré, M., Strande, L., 2014. Fuel potential of faecal sludge: calorific value results from Uganda, Ghana and Senegal. J. Water Sanitation Hyg. Dev. 4 (2), 223–230. http://dx.doi.org/10.2166/washdev.2013.055.

Naylor, R.L., Hardy, R.W., Bureau, D.P., Chiu, A., Elliott, M., Farrell, A.P., Forster, I., Gatlin, D.M., Goldburg, R.J., Hua, K., Nichols, P.D., 2009. Feeding aquaculture in an era of finite resources. Proc. Natl. Acad. Sci. 106 (36), 15103–15110.

Nguyen-Viet, H., Zinsstag, J., Schertenleib, R., Zurbrügg, C., Obrist, B., Montangero, A., Surkinkul, N., Koné, D., Morel, A., Cissé, G., Koottatep, T., Bonfoh, B., Tanner, M., 2009. Improving environmental sanitation, health, and well-being: a conceptual framework for integral interventions. EcoHealth 6 (2), 180–191. http://dx.doi.org/10.1007/s10393-009-0249-6.

Nikiema, J., Cofie, O., Asante-Bekoe, B., Otoo, M., Adamtey, N., 2013. Potential of locally available products for use as binders in producing fecal compost pellets in Ghana. Environ. Prog. Sustain Energy 33 (2), 504–511. http://dx.doi.org/10.1002/ep.11790.

Nikiema, J., Cofie, O., Impraim, R., 2014. Technological Options for Safe Resource Recovery from Fecal Sludge. International Water Management Institute (IWMI), CGIAR Research Program on Water, Land and Ecosystems (WLE).

Niwagaba, C., Nalubega, M., Vinnerås, B., Sundberg, C., Jönsson, H., 2009. Bench-scale composting of source-separated human faeces for sanitation. Waste Manag. 29 (2), 585–589. http://dx.doi.org/10.1016/j.wasman.2008.06.022.

Otterpohl, R., Braun, U., Oldenburg, M., 2003. Innovative technologies for decentralised water-, wastewater and biowaste management in urban and peri-urban areas. Water Science and Technology: A Journal of the International Association on Water Pollution Research 48 (11-12), 23–32.

Pescod, M., 1971. Sludge handling and disposal in tropical developing countries. Journal of Water Pollution Control Federation 43 (4), 555–570.

Pescon, B., Nelson, K., 2005. Inactivation of *Ascaris suum* eggs by ammonia. Environmental Science and Technology 39, 7909–7914.

Rice, A., Sacco, L., Hyder, A., Black, R., 2000. Malnutrition as an underlying cause of childhood deaths associated with infectious diseases in developing countries. Bull. World Health Organ. 78 (10), 1207–1221.

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), 9–15. http://dx.doi.org/10.1021/ef700267m.

Salminen, E., Rintala, J., 2002. Anaerobic digestion of organic solid poultry slaughterhouse waste—a review. Biores. Technol. 83 (1), 13–26. http://dx.doi.org/10.1016/S0960-8524(01)00199-7.

Seginer, I., Bux, M., 2005. Prediction of evaporation rate in a solar dryer for sewage sludge. Agricultural Engineering International: the CIGR Ejournal, VII https://ecommons.cornell.edu/bitstream/handle/1813/10438/EE%2005%20009%20Bux%20final%208Dec2005.pdf?sequence=1&isAllowed=y.

Shalabi, M., 2006. Vermicomposting of Faecal Matter As A Component of Source Control Sanitation. Institute of Wastewater Management and Water Protection, Hamburg University of Technology, Germany, http://tocs.ulb.tu-darmstadt.de/180983946.pdf.

Sharrer, M., Rishel, K., Taylor, A., Vinci, B.J., Summerfelt, S.T., 2010. The cost and effectiveness of solids thickening technologies for treating backwash and recovering nutrients from intensive aquaculture systems. Bioresource Technology 101 (17), 6630–6641. http://dx.doi.org/10.1016/j.biortech.2010.03.101.

Solids Handling Plan, 2010. Appendix K – Technical Memorandum 8 – Sludge Thickening Systems Evaluation. http://www.madsewer.org/Planning/Facility-Plans/SolidsHandlingPlan.

Song, Z., Qin, J., Yang, G., Feng, Y., Ren, G., 2012. Effect of human excreta mixture on biogas production. Adv. Mater. Res. 347, 2570–2575.

Still, D., Louton, B., Bakare, B., Taylor, C., Foxon, K.M., Lorentz, S.A. 2012. Investigating the Potential of Deep Row Entrenchment of Pit Latrine and Waste Water Sludges for Forestry and Land Rehabilitation Purposes: Report to the Water Research Commission. Water Research Commission.

Strande, L., Ronteltap, M., Brdjanovic, D., 2014. Faecal Sludge Management—Systems Approach for Implementation and Operation. IWA Publishing, London.

Strauss, M., Heinss, U., Larmie, S.A. 1998. Solids separation and pond systems for the treatment of faecal sludges in the tropics? Lessons learnt and recommendations for preliminary design. EAWAG/SANDEC.

Strauss, M., Larmie, S., Heinss, U., 1997. Treatment of sludges from on-site sanitation - Low-cost options. Water Sci. Tech. 35 (6), 129–136.

Strauss, M., Montangero, A., 2002. Faecal sludge management review of practices. In: Problems and initiatives. London and Duebendorf: DFID Project R8056, Capacity Building for Effective Decentralised Wastewater Management. Swiss Federal Institute of Aquatic Science (EAWAG), Department of Water and Sanitation in Developing Countries (SANDEC).

Suthar, S., 2007. Vermicomposting potential of *Perionyx sansibaricus* (Perrier) in different waste materials. Biores. Technol. 98 (6), 1231–1237. http://dx.doi.org/10.1016/j.biortech.2006.05.008.

TAC Report, 2013. Technical Assistance Consultant s Report? Bangladesh: Coastal Towns Infrastructure Improvement Project, Final report volume 4: annex–infrastructure, water resources. https://www.adb.org/sites/default/files/project-document/79300/44212-012-tacr-04.pdf.

Tilley, E., Ulrich, L., Luethi, C., Reymond, P., Zurbruegg, C., 2014. Compendium of Sanitation Systems and Technologies. Swiss Federal Institute of Aquatic Science and Technology (Eawag), Duebendorf, Switzerland.

Tomberlin, J.K., Sheppard, D.C., Joyce, J.A., 2002. Selected life-history traits of black soldier flies (Diptera: Stratiomyidae) reared on three artificial diets. Ann. Entomol. Soc. Am. 95 (3), 379–386.

Vinnerås, B., 2007. Comparison of composting, storage and urea treatment for sanitising of faecal matter and manure. Biores. Technol. 98 (17), 3317–3321.

WASHplus Project, 2011. Low Cost Systems for the Management of Sludge from Toilets and Shower Units. Connecticut Avenue, NW Washington, DC 20009-5721.

Werther, J., Ogada, T., 1999. Sewage sludge combustion. Progr. Energy Combust. Sci. 25 (1), 55–116. http://dx.doi.org/10.1016/S0360-1285(98)00020-3.

WHO, 2000. Global Water Supply and Sanitation Assessment. Geneva: World Health Organization. http://www.who.int/water_sanitation_health/monitoring/jmp2000.pdf.

WHO, 2002. Reducing risks. In: Promoting Healthy Life. WHO, http://www.who.int/whr/2002/en/.

WHO, 2004. The global burden of disease. http://www.who.int/healthinfo/global_burden_disease/2004_report_update/en/.

WHO, 2006. WHO Guidelines for The Safe Use of Wastewater, Excreta and Greywater. In: Excreta and Greywater Use in Agriculture, vol. IV. World Health Organization, Geneva.

Winker, M., Vinnerås, B., Muskolus, A., Arnold, U., Clemens, J., 2009. Fertiliser products from new sanitation systems: their potential values and risks. Biores. Technol. 100 (18), 4090–4096. http://dx.doi.org/10.1016/j.biortech.2009.03.024.

Wong, S.H., Griffiths, D.A., 1991. Vermicomposting in the management of pig-waste in Hong Kong. World Journal of Microbiology & Biotechnology 7 (6), 593–595. http://dx.doi.org/10.1007/BF00452837.

Yadav, K.D., Tare, V., Ahammed, M.M., 2010. Vermicomposting of source-separated human faeces for nutrient recycling. Waste Management 30 (1), 50–56. http://dx.doi.org/10.1016/j.wasman.2009.09.034.