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Title of the paper

Technology Options for Faecal Sludge Management in Developing Countries: Benefits and Revenue from Reuse

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Abstract

This article provides technology options for the treatment of Faecal Sludge (FS) in developing countries to minimize 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. Cost benefit analyses on different combinations of primary and sludge treatment technologies were conducted to analyse its techno-economic feasibility. The analysis was conducted across different classes of cities with varying population size. The combination of primary treatment technologies with lime stabilization sludge treatment technology emerged to be the most economically viable options for FS treatments across different population size in developing countries.

Keywords: Sanitation, Faecal Sludge, Technology, Decision Matrix, Benefits, Cost and Revenue

1. Introduction

Sanitation refers to the maintenance of hygienic conditions by proper treatment and disposal of excreta. Excreta consist of urine and faeces that are not mixed with grey water. It has low volume but high concentration of nutrients and pathogens. Inadequate sanitation is the chief cause of diseases worldwide, whereas improved sanitation is known to have a significant positive impact on human health (Lalander et al., 2013). 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 (Ahmed, 2012) and about 38% of the urban households in India use septic tanks as onsite sanitation facility (World Bank, 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% faecal coliform 85% *Escherichia coli* (*E. coli*) and 7% 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 1,000 Colony-Forming Units (cfu) 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 people 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 (Murray & Lopez, 1996). 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 (Prüss et al., 2002; WHO, 2002). Most of the deaths due to diarrhoea occur in children below age 5 in developing countries (WHO, 2000) . A higher risk of mortality has been observed in children with low weight (for their age) (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 minimizing 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 and metals as well as solid content and Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD) are excessively higher in FS. Safe disposal of FS helps to reduce water pollution and health hazards, and also reduces the burden of waste in the environment. 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; Nandimandalam, 2011). 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 sanitized, 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 in India, which aim to achieve cities free from open defecation.

The key objective of the study is to assess existing FS treatment technologies that may be relevant for adoption in developing countries to minimize exposure to FS for urban sanitation improvements, and also to understand the benefits of sanitation with respect to cost recovery. The second section of the paper discusses about the constraint and reuse potential of FS in developing countries. The third section analysed the technologies options for primary and sludge treatment and the fourth section discuss about the benefits. Fifth section provides detailed financial analysis 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 (Koné & Strauss, 2004)]. Sludge characteristics vary significantly depending on the location, water content and storage. For example, ammonium concentration in FS can vary from 300–3,000 mg/L, while 60,000 Helminth Eggs (HE) can be present per litre of FS (Mang & 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 stabilization of FS. Technologies for dewatering of FS have been reported previously (Pescod, 1971; Strauss et al., 1997; Strauss et al., 1998). Dewatering of sludge reduces transport loads and sludge with low moisture content is easier to handle. It 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 to 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 fertilizer 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 sanitization prior to use (Albihn & 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, etc. These low-cost treatment technology options **(Fig.1)** for FS have been found in the literature survey, books and document analysis.

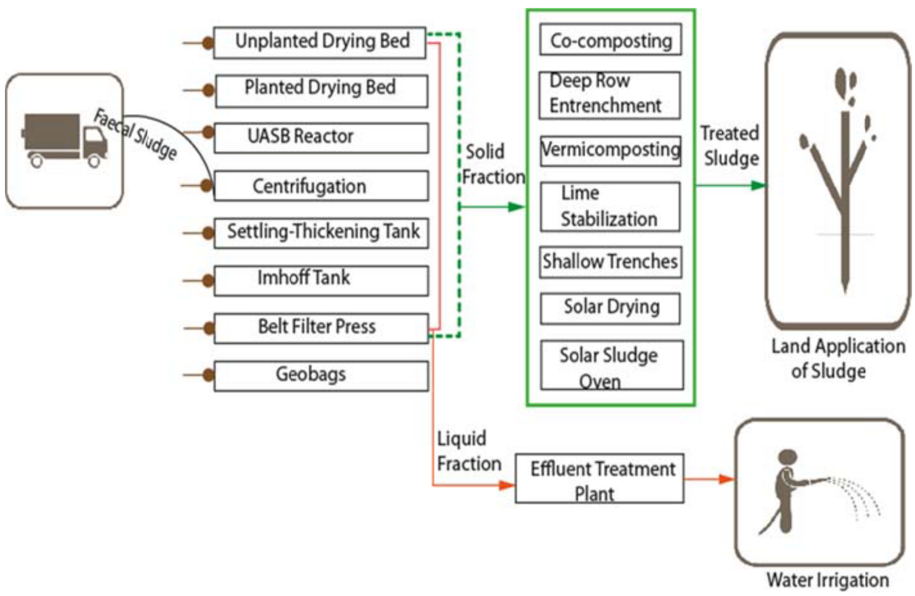

Fig.1. Overview of low-cost technology options for faecal sludge treatment.

These treatment technologies are generally appropriate for the household level, ward level and city level. Each technology has different fields of application. An initial examination of FS (which is discharged by collection and transport trucks) is required in several treatment methodologies before initiation of its treatment, due to presence of high content of coarse waste such as rocks, sand, iron, wood, textiles and plastics, tissue and paper. In order to avoid the chocking of pumps and other machineries and also to check debris in end produces it is very essential to screen the influent of treatment plants. Also, the characteristics of the FS collected at industrial and commercial facilities should be checked before treatment as they can be contaminated with metals, with higher concentrations of oil, grease and fats or other concern. 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 minimizes 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 stabilized FS.

After treatment, three types of end products will be produced, i.e., screenings, treated sludge and liquid effluents. The liquid effluent from the dewatering units must be treated further to meet the requirements for water reuse or discharge into the environment. Low-cost technologies such as waste stabilization ponds or wetlands could be used for the liquid treatment.

3. Technology for Primary and Sludge Treatment

3.1. Technology for Primary Treatment (Solid–Liquid Separation)

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 (UDB), Planted Drying Bed (PDB), Up-Flow Anaerobic Sewage Blanket (UASB) reactor, centrifugation, Settling and Thickening (S&T) Tank, Imhoff Tank (IT), geobag and Belt Filter Press (BFP). Out of these technologies, centrifugation, geobag and BFP would be used only for solid–liquid separation, whereas UDB, PDB, UASB reactor, IT and S&T 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.

Table 1 Overview and Removal Efficiency of Primary Treatment Options.

Treatment Option	Design Criteria	Removal Efficiency	Preferred Areas	Land Requirement
UDB	100–200 kg TS/ m^2/year	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)
PDB	≤ 250 kg TS/m^2/ Year, Solids Accumulation Rate (SAR): 20cm/year	SS:96–99%, COD: 95–98%, TS:70–80% (Koné & Strauss, 2004)	Peri-urban and rural areas.	4,000 m^2 /MLD
UASB Reactor	-	BOD: 60–90%, COD: 60–80%, TSS:60–85% (SSWM)	Urban areas (suited for densely populated areas)	600 m^2 /MLD
S&T tank	SAR: 0.13m^3/m^3 of raw FS HRT: ≥ 4 h	SS: 57%, COD: 24%, BOD: 12%, HE: 48% (Heinss & Strauss, 1999)	Urban and peri-urban areas	0.006 m^2/ capita (Koné & Strauss, 2004)
IT	-	SS: 50–70%, BOD (30–50%) (Barnes & Wilson, 1976)	Urban areas (suited for densely populated areas)	600 m^2 / MLD

3.1.1 Unplanted Drying Bed

Unplanted drying beds are used for dewatering and drying of FS (at volumetric ratios >2:1). They 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. The sludge from a UDB cannot be directly used for land application as a soil fertilizer due to the presence of pathogens.

The main advantages of a UDB 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.

3.1.2 Planted Drying Bed/Reed 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 PDBs for waste stabilization 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.

3.1.3 UASB Reactor

UASB rector treats FS and wastewater by anaerobic digestion and it has the potential to reduce the sludge volume as well as to produce biogas. The FS characteristics need to be checked before using the UASB reactor technology, as fresh or less stabilized FS will have higher concentrations of organic matter but will also contain inhibiting compounds. Digested FS, which is generated from the septic tank, is emptied every 2-3 years; this may not be appropriate for anaerobic co-treatment because of the sludge in the septic tank is partially digested. In this case, the low concentration of organic matter in the digested FS will lead to low biogas production but high solid accumulation, resulting in high operational costs with less benefits.

The UASB reactor technology has advantages in terms of nutrient recycling, energy balance and CO_2 emission. It also achieves a high reduction of BOD and low sludge production. This treatment requires a relatively high level of skills for Operation and Maintenance (O&M).

3.1.4 Settling–Thickening Tanks

A rectangular settling–thickening (S&T) 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) .

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.

3.1.5 ImhoffTank

Imhoff tank is a primary treatment system 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. Imhoff tanks usually consist of a two-storey tank mechanism that facilitates the sedimentation process in the upper storey and the anaerobic digestion of the settled particles in the lower storey (Crites & Technobanoglous, 1998) . The Imhoff tank provides a solution by separating the sludge from the effluent so that it may be degraded. Presently, developing countries are still using this treatment technique due to its lower maintenance cost and negligible energy inputs, other than hydraulic gradients.

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.

3.1.6 Centrifugation

Centrifugation is a type of mechanical dewatering that is mostly applied for the treatment of residual sludge in large-scale centralized wastewater treatment plants. 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). This technology uses centrifugal force for drying the FS by squeezing it outwards on the surface of a cylinder rotating on its horizontal axis. When the flocculated sludge is injected into the middle of this cylinder, it pushes the particles outward against the surface (Strande et al., 2014) .

Feedstock properties (sludge volume index and water-holding structure) and the rotational speed of the centrifugation bowl are factors on which the efficiency of the centrifugation process depends. 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.

3.1.7 Belt filter press

A belt filter press is a kind of mechanical dewatering system similar to centrifugation; it is used for the segregation of the solid and liquid parts from FS. Its only application is as a batch process and is commonly utilized in industrial applications and municipal wastewater facilities. There are three operational stages for the dewatering of the sludge: chemical conditioning, gravity drainage, and compaction in a pressure-and-shear zone. Solid wastes are squeezed by two porous belts for dewatering. Increase in pressure commences in the wedge zone where the two belts are pressed against each other, following the gravity zone. Pressure increases as the solids advance through the wedge zone and enter the high-pressure or drum pressure stage of the belt filter press (Nikiema et al., 2013). The solid loading rate and hydraulic loading rate of a belt filter press are 218–272 kg TS/h/m and 10–15 m^3/h/m, respectively (Nikiema et al., 2014). The sludge generated from the belt filter press cannot be directly discharged to the environment after the sludge-thickening process; co-composting should be done. Further treatment of the liquid stream, which is produced from dewatering, is required as it can be high in ammonia, salts, and pathogens.

The belt filter press technology requires lower energy (10–60 kWh per metric tonne of solid) compared with the centrifugation technology (20–300 kWh per metric tonne of solid). It is advantageous due to the relatively lower capital and operational cost required, but has a limitation due to difficult cleaning of the filter clothes.

3.1.8 Geobags

Geobags are used for dewatering of wet sludge. 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. This is a passive technique that does not need extensive and constant deployment of labour or frequent maintenance of equipment. This technique is also less time-consuming due to its capability of increasing the percent solids to about 22–27% in a comparatively lesser time period. This system has been well applied and has worked in Malaysia where several strategic locations have been equipped with geotube utilities, which in turn has reduced the expenditure incurred on the overall operations by 37% and enhanced the revenues by 35% (Dietvorst, 2012).

This technology is an economical option and requires minimal equipment. It needs a pump for filling of sludge and can run 24/7 with minimal labour.

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

Based on the primary treatment technological options, a decision matrix was prepared with respect to land requirement, energy requirement, skill requirement, CAPEX, OPEX and groundwater level **(Table 2)**. The decision matrix ascertains the favourability of a technology in comparison with other identified technologies. **Table 2** shows that the UDB, PDB and geobags have high land requirements but no energy requirement, while UASB reactor has high discharge standards but has a moderate CAPEX and OPEX. Whereas UDB, PDB, UASB reactor, centrifugation and BFP do not depend on the groundwater level for operation, for IT, S&T tank and geobags, the groundwater level should be deep **(Table 2)**.

Table 2 Decision matrix for primary treatment technology (solid–liquid separation).

Constraint	UDB	PDB	UASB reactor	Centrifugation	S&T	IT	BFP	Geobag
Land Requirement	+++	+++	+	+	+	+	+	+++
Energy Requirement	+	+	+	++	+	+	++	+
Groundwater Level (shallow/deep)	+	+	+	+	++	+++	+	+ +
CAPEX	+	+	++	+++	+	++	++	++
OPEX	+	+	++	+++	+	++	+	++
Skill Requirement	+	+	+++	++	+	+++	+++	+
Discharge Standard	++	++	+++	+	++	++	+	+
+: low favourability, ++: moderate favourability, +++: high favourability								

3.2. Technology for Sludge Treatment

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 composting, vermicomposting, deep row entrenchment, shallow trenches, solar drying, lime stabilization and solar sludge oven. Deep row entrenchment and shallow trenches can be considered as both a treatment and an end-use option.

3.2.1. Co-composting

Co-composting of FS and municipal solid waste is a biological process that involves microorganisms for the degradation of organic matter under aerobic conditions. 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 requires well-balanced conditions of moisture and aeration 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. This technology can be applicable at the household, neighbourhood and city levels. After composting, the resulting end product is stabilized organic matter that can be used as a soil conditioner. It also contains nutrients, which can have a beneficial effect as a long-term organic fertilizer. 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 co-composting technology can only be applicable when a source of well-sorted biodegradable solid waste is available.

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). The output of co-composting is a good soil conditioner and it provides a valuable resource that can improve local agriculture and food production. But this technology requires technical and managerial skills for operation and generation of safe products.

3.2.2. Deep Row Entrenchment

The use of pit sludge buried in deep rows in combination with tree plantations may provide a safe disposal option in denser peri-urban settlements, and at the same time enable the organic nutrients digested in the sludge to be used beneficially. This method limits the reuse of biosolids and effluent to uptake by trees and ground remediation. In the deep row entrenchment process, deep trenches are dug, which are then filled with sludge followed by covering with soil. 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 fertilizer for trees. Trees are then planted on top, which gain benefits from the organic matter and nutrients that are slowly released from the FS. 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.

In the application in Durban, limited nitrate leaching was found in the soil and tests conducted in the area showed that surrounding groundwater bodies remained free from pollution. It also appeared that the fast-growing trees took up the additional nutrients (Still et al., 2012). In Umlazi, Durban, eucalyptus trees were planted at a deep row entrenchment site. Deep row entrenchment was implemented for wastewater sludge in the United States in the 1980s and has been adapted for FS in Durban, South Africa (Still et al., 2012)

Deep row entrenchment is considered most feasible in areas where water is not directly obtained from a groundwater source and where sufficient land is available, which means the sludge would have to be transportable to rural and peri-urban areas. 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.

3.2.3. Vermicomposting

Vermicomposting is a low-cost technology system using earthworms for composting organic residues. 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). Earthworms promote the growth of bacteria and actinomycetes, and the growth of the latter is six times faster in the presence of earthworms and their content. C:N ratio determines the relative proportion of the mass of carbon to the mass of nitrogen in a 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 (*Eiseniafetida, Eiseniaandrei, Eudriluseugeniae, Perionyxexcavatus* and *Perionyxsansibaricus*) have been identified for the degradation of organic waste materials for vermicomposting (Wong & Griffiths, 1991; Suthar, 2007).

Shalabi (2006) found that faecal matter can be converted to mature compost by vermicomposting using two different earthworm species, namely, *E. fetida* and *Dendrobaenaveneta*, within 3 months if the temperature is kept between 20 and 30°C. Significant reduction in volatile solids from 820 ± 50 mg/g to 340 ± 20 mg/g (58% reduction) and dissolved organic carbon content from 25 ± 3 to 2.4 ± 0.43 mg/g (Yadav et al., 2010) indicates compost maturity, which means earthworms play an important role in the degradation of waste and produce a stable product (Contreras-Ramos et al., 2005).

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.

3.2.4. Lime Stabilization

Lime stabilization 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. Rise in pH, ammonia concentration and temperature through exothermic oxidation reactions are factors that control the process of pathogen reduction during alkaline stabilization (Pescon & Nelson, 2005). All chemical compounds with higher alkaline properties can be generally named as lime. Quicklime (CaO) and slaked lime $Ca(OH)_2$ are its most common forms. Quicklime is derived by a high-temperature calcination process of lime stone; hydration of quicklime then produces slaked lime, which is also termed as hydrated lime or calcium hydroxide.

Formation of $CaHCO_3$ increases the pH, which induces an environment that arrests or retards the microbial degradation of organic matter (Turovskiy & Mathai, 2006). In order to attain optimum results from the lime stabilization process in the most cost-effective way possible, it is significant to consider a number of design parameters like sludge characteristics, lime dose, contact time and pH (Turovskiy & Mathai, 2006). The main concern of this technology is the possibility of pathogen regrowth.

3.2.5. Solar Drying

Solar drying has been used for the treatment of wastewater sludge on a large scale since the nineteenth century in Europe and the United states (Hill & Bux, 2011). Treatment by solar drying is generally done in greenhouse structures with glassy covers, concrete basins and walls. Sludge is disposed into the concrete basins and processed for about 10–20 days. Options exist for batch or continuous operation, with devices to control the conditions in the greenhouses (e.g., ventilation, air mixing, temperature). The main factors influencing the evaporation efficiency in these systems are the solar variation, air temperature and ventilation rate, with the initial dry solid content of the sludge and air mixing also influencing the process (Seginer & Bux, 2005).

UV radiation is reflected by the glassy covers, which slightly reduces the efficiency of pathogen reduction, especially for faecal coliforms that are very sensitive to UV (Shanahan et al., 2010). Solar drying produces final dried solid content of about 40% after 12 days and 90% after 20 days of drying of FS as found under different conditions by Shanahan et al., (2010) and Hill & Bux (2011), respectively. Solar drying has high efficiency for dewatering and also 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.

3.2.6. 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. However, the main constraints of this technology are the space requirement and the need for regular groundwater monitoring.
Recent studies by the University of Durban showed that the shallow trench technique is safe for groundwater and that the sludge is beneficial to the growth of trees. The cost of a trench of 7.5 m^3 is US$10 (WASHplus Project, 2011).

3.2.7. Solar Sludge Oven

Solar Sludge Oven is an insulated box covered with glass that sits at a 45 degree 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. 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 utilized as a conditioner for the improvement of soil fertility in neighbouring orchards. The biological contamination of soil due to the application of sludge in the soil can be significantly reduced by this equipment. Local farmers can be convinced for using human excreta in their fields if the sludge could be properly dried by using appropriate techniques. The cost of two solar sludge ovens of 6 m^3 capacity is US$1,150 (WASHplus Project, 2011). 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.

3.2.8. Decision matrix for sludge treatment technology

Based on the sludge treatment technological options, a decision matrix was prepared with respect to land requirement, energy requirement, skill requirement, CAPEX, OPEX and groundwater level and discharge standard **(Table 3)**. The matrix shows that lime stabilization, shallow trenches and deep row entrenchment are low-cost options with respect to CAPEX and OPEX. Whereas composting, vermicomposting, and solar sludge oven do not depend on the groundwater level for operation, deep row entrenchment requires groundwater located deep **(Table 3)**.

Table 3 Decision matrix for sludge treatment technology.

Constraint	Co-Composting	Vermicomposting	Solar Sludge Oven	Lime Stabilization	Solar Drying	Shallow Trenches	Deep Row Entrenchment
Land Requirement	+++	+++	+	++	+++	+++	+++
Energy Requirement	+	+	+	+	+	+	+
Groundwater Level	+	+	+	++	++	++	+++

(shallow/deep)							
CAPEX	+++	+++	++	+	++	+	+
OPEX	+++	+++	+	+	++	+	+
Skill Requirement	+	++	++	++	++	+	+
Discharge Standard	+++	+++	+++	+++	+++	-	-
+: low favourability; ++: moderate favourability; +++: high favourability							

4. 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 stabilized sludge, can be used for different purposes such as biogas production, combustion as fuel, char production, in building materials and as a soil conditioner. Use of treated as well as raw sludge as a soil conditioner and fertilizer is very popular. Plant nutrients such as the nitrogen, phosphorus and potassium contained in human excreta are suitable as fertilizers, and the organics serve as soil conditioners. One adult per day excretes about 30 g of carbon (90 g of organic matter), 10–12 g of nitrogen, 2 g of phosphorus and 3 g of potassium. Generally in developing countries, farmers use wastewater, raw or treated sludge for irrigation and soil conditioning to minimize the purchase of chemical fertilizer. Recycled sludge and water might still contain pathogens. It is recommended that before use of wastewater and sludge for agricultural purposes, the characterization of the applied material be done.

4.1. Fuel production

Complete combustion of the organic substances in FS at high temperature by incineration is used for the generation of electricity. Energy production form wastewater sludge by incineration is common in Europe and the United States (Strande et al., 2014). Incineration destroys all pathogens present in the FS due to the high processing temperatures and reduces the sludge to ash (10% of its initial volume), which is mainly composed of the remaining inorganic material (Werther & Ogada, 1999). Muspratt et al., (2014)analysed FS from three cities and found that the calorific value of FS was 17.2 MJ/kg of dry solids (DS), which compares well with those of other commonly used fuels such as rice husks, 15.6 MJ/kg of DS, forest residues, 19.5 MJ/kg of DS, coffee husks, 19.8 MJ/kg of DS, and sawdust, 20.9 MJ/kg of DS. The sludge must be dried to 28% dry solids to get the net energy benefits (Muspratt et al., 2014). The average calorific value of FS dried at the experimental facility in Dakar was 12 MJ/kg of dry solids. This was lower than the overall average, most probably on account of the high content of ash (42%), which does not contribute to the calorific value.

4.2. Production of biochar

Thermochemical decomposition of faecal matter at elevated temperatures in the absence of oxygen is used for the production of biochar by pyrolysis. Absence of oxygen prevents combustion from occurring, and, hence, yields carbon-based end products that are different from those produced during incineration. These end products include (bio) char, oils and gases, the quantity of each depending on the processing temperature and the presence of gasifying agents. During pyrolysis, the temperature is maintained between 350 and 500°C, thereby yielding a larger quantity of char and gas with more compounds (e.g., CO_2 and CH_4). Both end products can be used as fuels, and the gases produced can also be recovered (Rulkens, 2008).

4.3. Biogas

FS produces biogas by anaerobic digestion and the amount of biogas production depends on operating parameters such as stability of the sludge, the COD of the sludge and temperature. Biogas can be used directly for applications such as cooking and fuel. However, electricity generation from biogas is not always practical on a small scale, and no full-scale operation has been identified in developing countries for the anaerobic digestion of FS in a centralized treatment.

4.4. Building materials

Dried FS can be used as a building material such as in the manufacturing of cement and bricks, and in the production of clay-based products, but would probably only be of interest in areas where raw materials are limited. The presence of pathogens in FS is not a concern because the high manufacturing temperatures kill the 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 (Jordan et al., 2005; Lin et al., 2012).

4.5. Soil conditioner

Generally FS used as a soil conditioner in developing countries. Compost, which is formed from the co-composting treatment, can be used to improve the soil structure, water-holding capacity, porosity and density (Winblad & Kilama, 1980). It also provides an amount of macro- and micronutrients, and may control or suppress certain soil-borne plant pathogens. Certain microorganisms found in compost suppress detrimental organisms like root-eating nematodes and specific plant diseases. FS contains a lower concentration of heavy metals than artificial manure, and can be considered a clean fertilizer. Since FS contains pathogens, the treatment of the faecal matter is necessary before it can be utilized as a fertilizer. 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).

5. Costs and Revenue from reuse

The final output of dried sludge manure is rich in nitrogen and phosphorous and can be used as a manure or soil conditioner. Since dried sludge is more hygienic in nature and has an improved structure, it has more market value. The practical implementation of any technology depends on its 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 **Table 4** and **Table 5**, the solid retention for the thickening and dewatering technologies like centrifuge, S&T tank and BFP is more than 80%, and, hence, these can generate more revenue. However, these technologies are more expensive than the other conventional technologies. 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 simple financial model was prepared to conduct a cost benefit analysis for different combinations of primary treatment and sludge treatment components. A financial assessment was performed for a 10-year-long period.

Table 4 Technical and Financial Parameters for each Primary Technology.

Primary technology	Solid retention capacity (%)	CAPEX (US$/KLD)	OPEX (US$/KLD)
UDB	35%[a]	445	13.34 [b]
PDB	30%[b]	474	14.22 [b]
UASB reactor	8%	741	44
Centrifugation	92%[b]	25,166	9,764[e]
S&T tank	95%[c]	799[f]	0.06 [f]
IT	50%[d]	741	44.45
BFP	85% [b]	2,174 [f]	17.45 [f]
Geobags	12.5%	1,226 [f]	244.37[f]

[a] Unplanted Drying Beds
[b] Nikiema et al., 2014
[c] Thickening Ponds
[d] Ajibade, 1999
[g] Solids Handling Plan, 2010
[h] 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]	5,458[c]	775 [c]
Vermicomposting	25% [a]	6,549 [c]	930 [c]
Lime stabilization	40% [a]	5.97[d]	7.16 [d]
Solar drying	31.6%[b]	877.55[b]	50.87 [b]
Shallow trenches	-	2.25[e]	0.00
Deep row entrenchment	-	2.25	0.00[a]
Solar sludge oven	32%	95.8 [e]	0.96[f]

[a] AIT Tool, 2016
[b] Chavez, 2013
[c] IL&FS Ecosmart Limited & M/s Organophos, 2009
[d] Wang et al., 2007
[e] WASHplus Project, 2011
[f] Kurt et al., 2015

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

Yield factor: The yield factor from each technology directly affects the quantity of manure produced, which in turn affects the revenue generated. In case of sludge treatment technologies, the yield factor from the compost plant is about 25%, whereas the lime stabilization plant has a yield of about 40%. 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. 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. **Table 6** shows the categorization of Indian cities.

Table 6 Categorization 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	5,000–9,999
VI	Less than 5,000

A simple financial analysis was conducted to calculate the Internal Rate of Return (IRR) and payback period of the project. **Table 7** shows the basic assumptions used for performing the cost benefit analysis. 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.

Table 7 Assumptions used in the financial model.

Parameters	Value
Inlet total solids	22000 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%

All the eight primary technologies were technically compatible with the seven sludge treatment options. Hence fifty-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 a primary treatment technology with different combinations of sludge treatment technologies. PDB was chosen as the primary treatment technology and combined with the seven 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 PDB with lime stabilization generates highest revenue among the seven combinations. Co-composting, vermicomposting solar drying and solar sludge oven are costlier and generate low yield as compared with the other sludge treatment options.

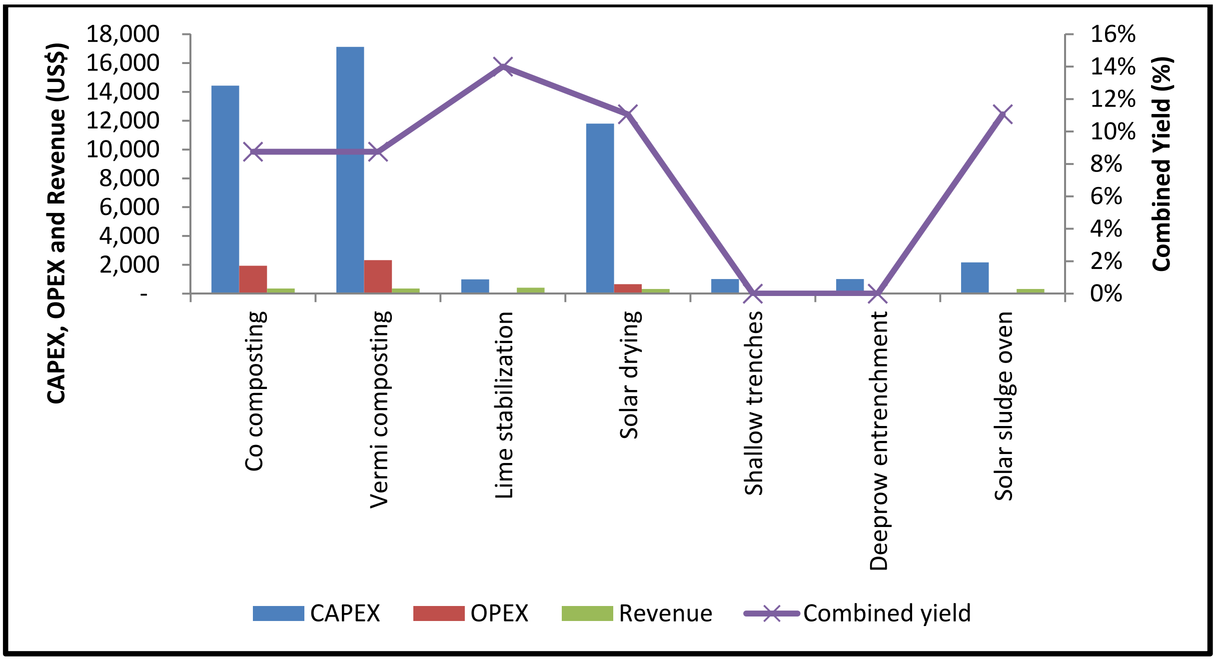

Fig.2. Variation in financial parameters generated from a planted drying bed with the seven sludge treatment options.

To understand the effect of population size on the economic analysis of the treatment plant, the model was run for population sizes based on the classification of Indian cities. Technologies generating an IRR of more than 10% were considered economically feasible. **Table 8** shows the various techno-economically feasible options against various population sizes.

Across several online shopping websites, the price of compost was found to vary from US$ 0.074 to 2/kg. Hence, a scenario analysis was conducted with an average price of the compost (ie, US$ 1/kg). The price of compost and other manure was increased by 10 times from the baseline and the feasibilities of the treatment technologies were checked. **Table 9** shows the various techno-economically feasible options against various population sizes for the escalated price of revenue (Scenario 1).

The baseline scenario generated 76 economically feasible options as shown in **Table 8**. Lime stabilization and solar sludge oven were the financially viable sludge treatment options in this scenario. The project IRR varied from 10-67% for a population size of 10,000 and went up to 31,426% for a population size of 5 million. The payback period of the treatment combinations with solar sludge oven as the sludge treatment option reduced from 8 years to 3 years.

With the increase in price of the compost and manure, scenario 1 generated 166 economically feasible options as seen in **Table 8**. The financially viable sludge treatment options in scenario 1 are co-composting, lime stabilization, solar drying and solar sludge oven. The project IRR varied from 10-634% for a population size of 10,000 and went up to 314,216% for a population size of 5 million.

Table 8 Techno-economically feasible options in the baseline scenario.

Primary treatment technologies	Population size					
	10,000	20,000	50,000	100000	10,00,000	50,00,000
UDB	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization
	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven
PDB	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization
		Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven
UASB reactor			Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization
				Solar sludge oven	Solar sludge oven	Solar sludge oven
Centrifugation				Lime stabilization	Lime stabilization	Lime stabilization
				Solar sludge oven	Solar sludge oven	Solar sludge oven
S&T tank	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization
	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven
IT	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization
		Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven
BFP	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization
		Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven
Geobags				Lime stabilization	Lime stabilization	Lime stabilization
				Solar sludge oven	Solar sludge oven	Solar sludge oven

Table 9 Techno-Economically Feasible Options in Scenario 1.

Primary treatment technology	Population size					
	10,000	20,000	50,000	1,00,000	10,00,000	50,00,000
UDB	Lime stabilization	Cocomposting	Cocomposting	Cocomposting	Cocomposting	Cocomposting
	Solar drying	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization
	Solar sludge oven	Solar drying	Solar drying	Solar drying	Solar drying	Solar drying
		Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven
PDB	Lime stabilization	Cocomposting	Cocomposting	Cocomposting	Cocomposting	Cocomposting
	Solar drying	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization
	Solar sludge oven	Solar drying	Solar drying	Solar drying	Solar drying	Solar drying
		Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven
UASB	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization	Cocomposting	Cocomposting
	Solar sludge oven	Solar drying	Solar drying	Solar drying	Lime stabilization	Lime stabilization
		Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar drying	Solar drying
					Solar sludge oven	Solar sludge oven
Centrifugation			Lime stabilization	Lime stabilization	Cocomposting	Cocomposting
			Solar sludge oven	Solar drying	Lime stabilization	Lime stabilization
				Solar sludge oven	Solar drying	Solar drying
					Solar sludge oven	Solar sludge oven
S&T tank	Co composting	Co composting	Co composting	Co composting	Cocomposting	Cocomposting
	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization
	Solar drying	Solar drying	Solar drying	Solar drying	Solar drying	Solar drying
	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven
IT	Lime stabilization	Co composting	Co composting	Co composting	Cocomposting	Cocomposting
	Solar drying	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization
	Solar sludge oven	Solar drying	Solar drying	Solar drying	Solar drying	Solar drying
		Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven
BFP	Lime stabilization	Lime stabilization	Co composting	Co composting	Cocomposting	Cocomposting

	Solar drying	Solar drying	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization
	Solar sludge oven	Solar sludge oven	Solar drying	Solar drying	Solar drying	Solar drying
			Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar sludge oven
Geobags	Lime stabilization	Lime stabilization	Lime stabilization	Lime stabilization	Cocomposting	Cocomposting
	Solar sludge oven	Solar drying	Solar drying	Solar drying	Lime stabilization	Lime stabilization
		Solar sludge oven	Solar sludge oven	Solar sludge oven	Solar drying	Solar drying
					Solar sludge oven	Solar sludge oven

From the baseline and revenue escalated scenario, it can be seen that the lime stabilization treatment option is the most feasible sludge treatment options across all population size. In the baseline scenario, it generates an IRR between 20% and 31,426% based on various population sizes. Similarly, the payback period of treatment plants using lime stabilization sludge treatment is low as compared with that of other technologies. **Fig.3** and **Fig.4** show a reducing trend of the payback period with increase in population size. The maximum payback period calculated in the baseline case and Scenario 1 was 8.84 and 2.77 years, respectively.

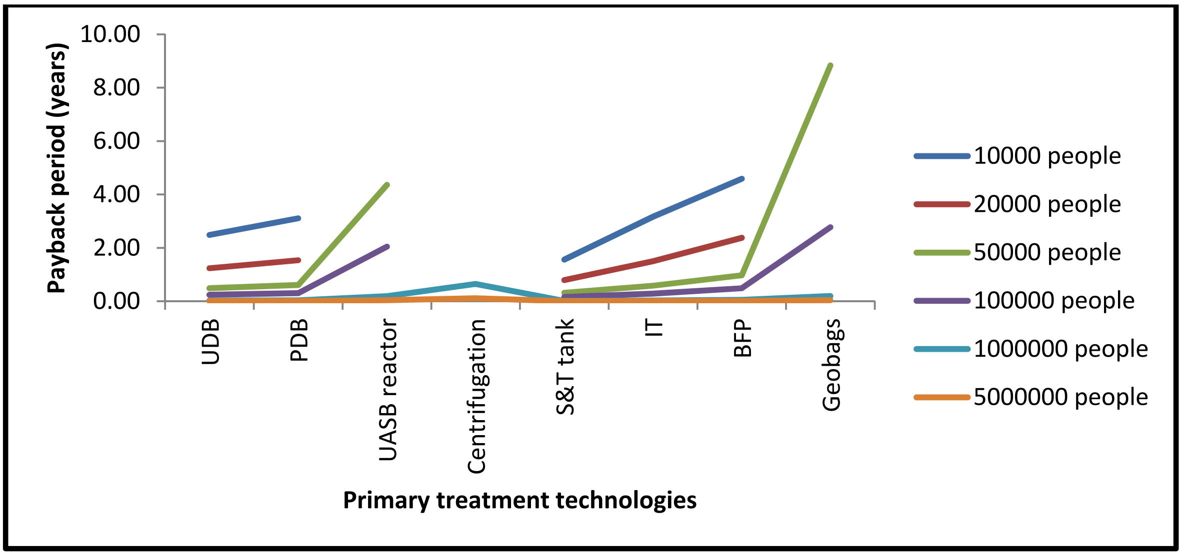

Fig.3. Payback period for combinations of primary technologies with the lime stabilization technology (baseline case).

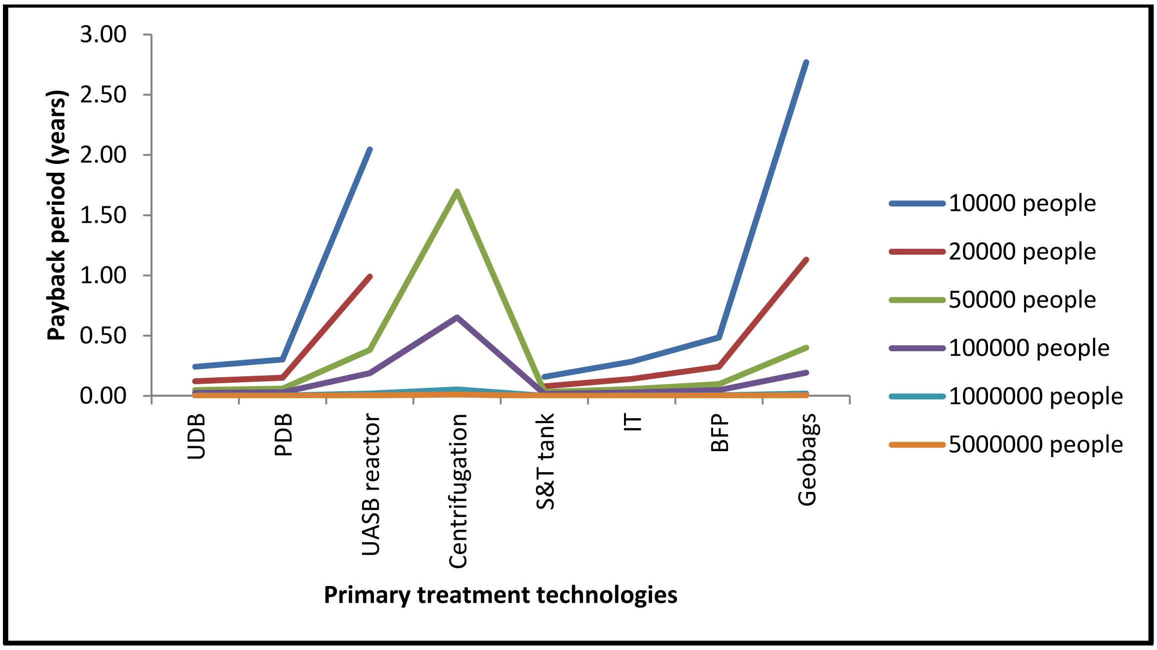

Fig.4. Payback period for combinations of primary technologies with the lime stabilization technology (Scenario 1).

As the population size increases, the choices of economically viable technology combinations increased in baseline scenario and Scenario 1. In the baseline scenario, lime stabilization and solar sludge oven became a feasible option for population sizes above 1,000,000 for all the eight primary treatment technologies. Similarly, co-composting, lime stabilization, solar drying and solar sludge oven became the feasible option in case of Scenario 1. 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 1,000,000 in case of Scenario 1 and baseline scenario. Hence, Class-IA and IB cities will have better options for economically viable FS treatment methods.

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 UASB, 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.

6. Conclusion

Rapid urbanization 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 utilized 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. The decision matrix was prepared for the primary and sludge treatment option with respect to land requirement, energy requirement, groundwater level, capital and operational cost, skill requirement and discharge standard. The decision matrix in the primary and sludge treatment technology option shows that UDB, PDB, geobags, co-composting and vermicomposting have high land requirements but do not need energy. These 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. Lime stabilization is the most techno-economic 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 PDB, UDB, UASB reactor, S&T tank, IT and BFP 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 fertilizer.

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Highlights for the paper

- Faecal sludge waste is generated from septic tanks; it causes environmental pollution and outburst of diseases.
- Technology options for faecal sludge management.
- The decision matrix prepared for the technology option with respect to land requirement, energy requirement, groundwater level, capital and operational cost, skill requirement and discharge standard.
- IRR and payback period was used as indicator to assess the economic viability of treatment technologies.
- Using faecal sludge as a valuable product could help to address both the sanitation challenge as well as offer environmental benefits in terms of organic fertilizer.