Review Paper

Improved and promising fecal sludge sanitizing methods: treatment of fecal sludge using resource recovery technologies

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ABSTRACT

The global challenges that face sustainable sanitation services in developing countries are the lack of fecal sludge (FS) management; this is due to the rapid urbanization and population growth as it generates enormous quantities of fecal sludge. The extensive use of unimproved sanitation technologies is one of the main reasons for environmental and public health concerns. In dispersed rural areas, isolated slums or in urban areas where a sewerage system is costly, a decentralized wastewater system can be used. Therefore centralized management of decentralized wastewater systems along with proper institutional framework treatment of fecal sludge can be used to enhance the economies of developing countries from resource recovery. The discovery of new ways to inactivate pathogens contained in human waste is key in improving access to sanitation worldwide and reducing the impact of conventional waste management processes on the environment. The entire FS management system should include on-site sanitary treatment methods, collection, and transportation of FS, treatment facilities as well as resource recovery or disposal of the treated end products. This review paper addresses the hygienization of fecal sludge and improved treatment technologies for safe reuse or disposal of the end products and the significant economic revenues attained from the treatments of fecal sludge.

Key words | fecal sludge, lactic acid treatment, lime treatment, solar septic tank, volatile fatty acid treatment

HIGHLIGHTS

● The use of resource recovery technology for fecal sludge treatment.
● Onsite treatment of fecal sludge.
● Effective and promising treatment of fecal sludge with improved technologies.
● The applicability of fecal sludge for soil enhancement for crop production.
● How to recover resource from sludge.

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INTRODUCTION

Sustainable Development Goal number six of the United Nations aims to achieve universal access to ‘safely managed’ sanitation by 2030. Safely managed sanitation is described as the use of improved facilities with safe disposal in situ or offsite transportation and treatment (Borja-Vega et al. 2019). Fecal sludge (FS) refers to raw, slurry, or partially digested excreta with or without the combination of gray water that originates from on-site sanitation systems, such as pit latrines, septic tanks, and dry toilets. FS resembles a solid and highly differs in characteristics and consistency (Lindberg & Rost 2018). FS management (FSM) is challenging due to the lack of accessible sanitation facilities in developing countries (Singh et al. 2017).

As of April 2020, approximately 93% of the world’s population (nearly 7.2 billion people) live in countries with restrictions on movement (Lindberg & Rost 2018). The new coronavirus disease, officially named COVID-19 by the World Health Organization (WHO), has triggered a global pandemic with drastic changes in many aspects of human life. The name of the new virus was announced on February 11, 2020, by the International Commission on Taxonomy of Viruses as severe acute respiratory syndrome coronavirus 2 (Singh et al. 2017).

COVID-19 is a global crisis compared with previous pandemics in history. Healthcare systems of some of the most advanced countries in the world are on the verge of collapse. The world is currently undergoing unprecedented social and behavioral changes due to the threat of COVID-19. Among these changes are indispensable basic services of waste collection and treatment. Safe transportation and treatment of FS can play a major role in reducing infectious disease transmission (Hellmér et al. 2014; Gorbalenya et al. 2020).

Transporting fecal waste to treatment plants is necessary to reduce the impact of fecal-oral pathogens because exposure to such pathogens is associated with negative effects on human health and survival (Abdoli & Maspi 2018; WHO 2018). Thus, attaining sustainable development goals (SDGs) on sanitation will require the provision of safe and hygienic services in FSM that depend on on-site sanitation technologies (Peal et al. 2014; Berendes et al. 2017; Scott et al. 2019).

The availability of safe water and adequate management of human waste is a major global challenge and one of the main objectives of the United Nations for sustainable development. One-third of the world’s population (2.4 billion people) do not have access to improved sanitation (WHO/UNICEF 2014). Developing countries and emerging economies are heavily dependent on on-site waste treatment, such as septic tanks or pit latrines. The need for safe sanitation is remarkable because 2.7 billion people are currently dependent on on-site sanitation, and this figure is expected to rise to five billion by 2030 (Forbis-Stokes et al. 2016). Although considered rural or temporary solutions, on-site sanitation systems have become increasingly important for urban populations because one billion people living in urban areas of Africa, Asia, and Latin America use on-site treatment systems.

Approximately 65–100% of sanitation services in urban areas of sub-Saharan Africa are performed via on-site treatment systems (Strande 2014). On-site sanitation is needed for growing urban populations because the implementation of existing centralized wastewater collection and treatment systems in developed countries are overly expensive and complex and consume excessive water and/or energy in poor and less developed countries (Lalande et al. 2013a, 2013b; Mara 2013). Given that the demand for improved water supply and sanitation grows globally, treatment technologies that minimize waste and consumption of water and allow water reuse should be considered to achieve SDGs (Gijzen 2001; Katukiza et al. 2012).

Human feces are a natural fertilizer that can replace chemical or mineral substances (Factura et al. 2011; Andreev et al. 2018). Human feces can play a pivotal role in increasing soil fertility to enhance the crop production due to their nutrient contents (Kimetu et al. 2004). However, the presence of high concentrations of pathogens and various harmful organisms in feces can affect the soil and crops (Andreev et al. 2018). Therefore, hygienization of FS is important before using it as a fertilizer to increase the sustainability of soil fertility for agricultural production.

Many technologies are available for the safe management of excreta in the sanitation service chain. Pit latrines, septic tanks, and sewered systems can ‘safely
manage' excreta, as defined by the SDG. Safe management of household excreta is the containment, collection, and transport of excreta to specified disposal or treatment sites or the safe reuse of excreta depending on local conditions at the household or community level (Anderson et al. 2015). Figure 1 depicts the service chain of safely managed excreta.

In developing countries, there is a growing interest and awareness of FSM issues which is substantiated through several types of research and projects that have occurred in fecal sludge management. In many developing countries the management of fecal sludge is very poor as it is not properly managed. Several reasons could be addressed for the improper management, perhaps due to the lack of institutional framework, lack of awareness on the effect of poor sanitation, lack of required knowledge to initiate and implement FSM programs, and lack of improper sanitation infrastructures and designing of fecal sludge treatment plants.

This can lead to unsatisfactory operation of on-site sanitation facilities (OSF), overflowing septic tanks and pit latrines as well as unsafe emptying of pit latrines, and discharge of untreated pathogenic fecal sludge into the environment. Therefore this review mainly aims to determine the hygienization of FS, improved treatment technologies for the safe reuse or disposal of FS, and significant economic revenues attained from the treatment of FS.

Globally, the treatment of FS and its benefits in agriculture have attracted substantial interest from researchers. Nevertheless, many publications have focused on the various uses of FS without considering the problems associated with the collection, transportation, and stabilization processes. In addition, a comprehensive overview of the problems faced by FSMs and new technologies for them is still lacking. This article attempts to fill this gap by reviewing the current advances in research and challenges related to FSM technologies.

The focus is on the problems associated with the collection, transport, and disposal of FS, where the need for improvement is most evident, as well as several treatment processes. There are important points to be considered when selecting treatment technologies; there are different technologies for different treatment purposes, and they can be used alone and/or in combination. There are many factors to consider when selecting the best treatment configurations, including the end-use, treatment goals, potential benefits and limitations, and how to compare costs.

**Fecal Sludge Characterization**

Common factors required to characterize FS are chemical oxygen demand (COD), biochemical oxygen demand, solid concentration, nutrients, pathogens, and metals. FS generally demonstrates 10–100 times higher concentrations of organic matter, total solids, ammonium, and helminth eggs than sewage sludge. FS can be classified as digested and fresh and as high, medium, and low strength on the basis of COD and total nitrogen (TN) concentrations, respectively (Zakaria et al. 2017). Concentration values of fecal strength in the literature are listed in Table 1.
The use of pathogen inactivating action of uncharged ammonia (NH₃) can be used as a treatment option for FS (Park & Diez-Gonzalez 2003; Nordin et al. 2009). The treatment of FS using ammonia can efficiently inactivate bacteria, viruses, protozoa, and helminths (Rehrah et al. 2016). Ammonia demonstrates a potential self-sanitizing effect that can be found in the degradation of urea (Harroff et al. 2019).

Silva et al. (2015) revealed that ammonia from urine can serve as a mechanism for pathogen inactivation, which is strongly related to the ammonia concentration. Pathogen reduction in FS occurs with ammonia because ammonia enters cells, takes up intracellular protons to form ammonium (NH₄⁺), and disrupts the functioning of organisms in the form of charged ions (Favas et al. 2016; Karunanithi et al. 2016).

The amount of ammonia varies in different toilets. Most of the organic energy in domestic wastewaters is found in source-diverted black water so to maximize energy recovery the wastewater can be treated anaerobically. The black water collected from different water-saving option toilets like conventional, dual, and vacuum toilets represents different concentrations of ammonia. A study conducted by Mengjiao et al. (2019) revealed that the initial free ammonia concentrations for vacuum toilet (1 L water/flush), dual flush toilet (6 L water/flush), and conventional toilet (9 L water/flush) collected from black water at 35 °C were 393, 60, and 26 mg L⁻¹ respectively (Gao et al. 2019).

The ammonia concentration in pit latrines without flush water is high but can be lost when pits are ventilated due to the volatile nature of ammonia. By comparison, the ammonia concentration in pour flush latrines is less mainly due to the flush water. Ammonia treatment is applicable to FS from vacuum toilet pour-flush latrines with very low water use. Airtight storage should be used efficiently by treating FS using ammonia to avoid the loss of concentration (Christiaens et al. 2017).

Alkaline stabilization is the process of adding ammonia to wastewater sludge (Nagy & Zseni 2017; Lohman et al. 2020). Human excreta has been investigated for the extraction of ammonia, which can be used for pathogen reduction in FS. Urine can be collected separately and applied to FS to inactivate pathogens due to its high concentration of ammonia. If the ammonia concentration is low in the sludge, then synthetic urea can be added to enhance the treatment (Chávez et al. 2019).

The high solubility of ammonia (NH₃) in water and lipids increases ammonia transport through cell membranes and other cell walls via diffusion. The addition of ammonia will increase the internal pH, disrupt the membrane, and cause the bacterial membrane and cell proteins to degenerate. Hence, the cell of the pathogen will disintegrate and destruct further, ammonia gas rapidly alkalinizes the cytoplasm and causes cell damage. Ammonia treatment

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**Table 1 | Defined COD, TN and TSS concentrations for faecal sludge strength (Dangol 2013)**

| Sludge type | Strength  | COD (mg/L) | Total N (mg/L) | TSS (mg/L) |
|------------|-----------|------------|----------------|------------|
| Fresh      | High      | 250,000    | 5,000          | 100,000    |
|            | Medium    | 65,000     | 3,400          | 53,000     |
|            | Low       | 10,000     | 2,000          | 7,000      |
| Digested   | High      | 90,000     | 1,500          | 45,000     |
|            | Medium    | 45,000     | 400            | 25,000     |
|            | Low       | 3,000      | 200            | 1,500      |

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**OVERVIEW OF TREATMENT TECHNOLOGIES OF FECAL SLUDGE**

Various characteristics of FS make it challenging for treatment. FS must not be discharged into surface water or disposed of in a landfill or treated as wastewater and solid waste due to the presence of excessively high concentrations of contaminants and its high moisture content. Therefore, FS cannot be used in agriculture to enhance production without further treatment. Stabilization of FS must be performed first and its solid and liquid matter must be separated to facilitate treatment (Rashed & Hithnawi 2006).

The liquid portion of FS can be processed using wastewater treatment technologies, whereas the solid portion is treated to improve its properties either for agriculture reuse or disposal. Available treatment technologies can be used depending on community context and treatment purpose. Properly treated FS can be used efficiently as a sustainable fertilizer in agriculture. Several treatment technologies are used to sanitize the content of pathogenic microorganisms found in FS (Mawioo et al. 2016).

**Intrinsic ammonia**

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requires less demanding storage conditions than lime treatment and is suitable for areas with urine-diverting dehydrating toilets. If synthetic urea is applied, then the cost may increase and potentially limit the sustainability of this treatment technology (Hill et al. 2013).

**Treatment of fecal sludge using lactic acid fermentation**

Fermentation is a traditional method of processing foods in today’s modern diet. Fermented foods are produced during the biotransformation of raw materials into end products through the actions of microorganisms. The majority of food biotransformation is dependent on ethanol fermentation by the yeast *Saccharomyces cerevisiae* or lactic acid fermentation with a broad range of bacteria called lactic acid bacteria (LAB) (Papadimitriou et al. 2013). LAB has been used in earlier studies for its remarkable role in food fermentation and its uses in human health (Tremonte et al. 2017).

Lactic acid pretreatment utilizes a fermentation process widely applied in food preservation, silage preservation, and management of different biowaste materials, such as kitchen waste (Li et al. 2014). LAB easily converts degradable carbohydrates into lactic acid and other metabolic byproducts. The sterilizing nature of the lactic acid compound and the production of antimicrobial compounds are factors that inhibit the pathogen growth in FS (Liu et al. 2015; Saa et al. 2019). LAB increases the acidification process in FS by reducing the pH. This reduction can inhibit the growth of bacteria, which are responsible for the unpleasant odor (Mozzi et al. 2013).

The presence of chelating agents and inhibitory activity of metabolites produced by LAB can be extended to pathogenic organisms. A pH of less than 2.5 is required to kill bacteria. However, the reduced rate of survival of bacteria at a pH of less than 3.5 indicates that the key antimicrobial property of lactic acid can reduce the intracellular rather than extracellular pH of bacteria. Therefore, the use of lactic acid to disinfect FS may be an appropriate method to inactivate pathogens. Bacterial pathogens in FS can be significantly reduced with a simple sanitation method that preserves nutrients and requires minimal infrastructure investment (Saa et al. 2019).

Lactic acid, which is produced during the fermentation of food waste, can be successfully and effectively used to inactivate pathogens that are found in FS. Pathogenic microorganisms, such as bacteria, viruses, fungi, parasitic protozoa, helminths, and pests, are present in FS (Van Asperen et al. 1998; Mozzi et al. 2013; Hu et al. 2017; Dias et al. 2018). Pathogens are mainly found in raw fecal matter, final effluent, and water environments (Baggi et al. 2001).

These microorganisms in FS can cause a variety of pathologies. For example, the consumption of water contaminated with feces, which is a serious global problem, can cause considerable human health risks, including diarrhea, hepatitis, and fever (Hewitt et al. 2011). The global consumption of poor-quality water causes an annual death of three million people, with the majority under the age of five years (Wang et al. 2016). Waterborne diseases have become a serious problem because the fecal matter is used directly as a fertilizer and FS is a potential spreader of pathogenic microorganisms (Simmons & Xagoraraki 2011).

The average per capita production of human excrement of approximately 550 kg/year (50 kg of FS and 500 kg of urine) includes various chemicals, such as around 7.5 kg of phosphorus, nitrogen, and potassium as well as some micronutrients useful for plant growth; the daily feces production can significantly vary depending on dietary habits (Ercumen et al. 2017; Dongzagla et al. 2021). Several studies revealed that fermentation is more efficient and faster in reducing pathogen load in FS than composting. Liu (2016) inactivated FS pathogens by composting for a long time and found that although enterococci and coliform were reduced, a small amount of residual concentration remained in the mature compost.

**Treatment of fecal sludge using lime**

Lime stabilization of FS is a simple and cost-effective chemical treatment process. Previous studies demonstrated that FS treatment using lime significantly reduces harmful pathogenic microorganisms and allows the sludge to function as a soil conditioner (Mignotte-Cadiergues et al. 2007; Maya et al. 2019). Lime is easy to apply and also provides an alkaline environment, which is hostile to biological activity.
The main constraint of this technique is the concern of pathogen regrowth.

A pH above 12 can disrupt the cell membrane of harmful pathogens, supply high levels of ammonia, and contribute to the removal of hazardous pathogens by functioning as a biocide. FS treatment using lime can effectively reduce salmonella and total coliforms (Mignotte-Cadiergues et al. 2003). The inactivation of helminth eggs is highly dependent on the storage life of lime-treated sludge (Foote et al. 2011).

The effect of the application of liming on microorganisms is partially related to the amount of lime added and some factors, such as sludge characteristics, total solids, pH, contact time liming, lime dose, and moisture content of the sludge, which must be considered (Jamal et al. 2018). Other factors affecting the treatment process include the rate of pH increase, lime quality, and extent of mixing. Figure 2 shows the powdered lime used to treat FS.

Reusing sludge treated with lime is advantageous because the health risk to humans is reduced due to the destruction of pathogens. FS stabilized by lime improves soil characteristics, such as texture and water retention capacity, and increases the pH of acidic soils, which is favorable to plant growth (Jamal et al. 2018).

However, stabilization of FS using lime can decrease soluble phosphate and total Kjeldahl nitrogen concentrations, which in turn reduces the agricultural value of the sludge (Kania et al. 2019). The addition of lime to increase the pH of FS results in nitrogen losses during the formation of gaseous ammonia (Gyawali 2018). Moreover, the amount of sludge fails to reduce through liming but the sludge volume increases by approximately 15–50% (Jamal et al. 2018). Total solids of the sludge will increase when lime is added as a treatment method because it dries rapidly (Greya et al. 2016).

Volatile fatty acid treatment for pathogen inactivation

High temperatures are commonly necessary to improve the rate of sludge stabilization and increase pathogen reduction. Pathogens are also exposed to high concentrations of organic acids. The effectiveness of organic acids is dependent on the concentration, pH, temperature, duration of exposure, and sensitivity of certain types of pathogens (Cardeña et al. 2017).

These factors, alone or in combination, can impact microorganism damage during anaerobic digestion (AD). The degree of pathogen inactivation through volatile fatty acids varies depending on the sensitivity of microorganisms. Organic acids inhibit microorganism growth due to their ability to penetrate the cell membrane, dissociate in the inner alkaline part, and acidify cell cytoplasm (Seol et al. 2019). In addition, laboratory cultures of Escherichia coli showed that bacteria support slightly alkaline intracellular pH (Tao et al. 2016).

Temperature affects the composition of the cell membrane. Cell components, namely proteins, lipids, and carbohydrates, are responsible for the cell transport phenomena and can survive a narrow temperature range. An increase in temperature beyond the usual temperature of the membrane may change its molecular structure. Therefore, fluidity of the cellular membrane may increase to allow the rapid diffusion of organic acids into the cytoplasm (Ding et al. 2017). Meale et al. (2015) revealed that high-temperature treatment using volatile fatty acids significantly reduces Clostridium perfringens concentrations than mesophilic temperatures. The degree of pathogen reduction can vary depending on the concentration of organic acid, temperature, and pH.

Co-composting

Co-composting is used extensively to process human feces separated from the source (WHO 2006; Torgbo et al. 2018). The partially treated sludge is mixed with organic solid waste fraction after dewatering FS. Well-balanced aeration
and moistening conditions are required for the survival of microbes in the composting process. Moisture and nutrient contents of FS is high, while municipal solid waste is rich in organic content. The end product is stabilized with the addition of organic matter after the composting process for use in agriculture as fertilizer.

The use of compost in agriculture can help stop the trend of land degradation (Furlong et al. 2017). Compost contributes to the replenishment of soil organic matter and thus improves its biological, chemical, and physical properties (Jara-Samaniego et al. 2017; Wong et al. 2017). Moreover, composting can inactivate pathogens by generating heat during the process, and the temperature decreases gradually until the compost is matured. Co-composting treatment is advantageous because it can reduce many pathogens and possibly remove helminth eggs.

**IMPROVED APPROACHES OF FECAL SLUDGE TREATMENT TECHNOLOGIES**

Innovative approaches in terms of infrastructure, technology, and cost recovery are required to solve sanitation challenges. The development of the sanitation service chain is primarily hindered by the lack of profitable or financially feasible options that can help manage the service chain. Innovative approaches toward sanitation are developed to recover energy from on-site waste systems using different processes, such as incineration (Hawkins et al. 2019), gasification (Sowale et al. 2019), smog (Yermán et al. 2015), and hydrothermal carbonization (Schüch et al. 2019). Key indicators of biomass feedstock utility include total solid (TS) content and calorific value. The TS and/or calorific value of FS causes significant technical constraints in recovering energy and determines the economic viability of FS as a fuel.

Septic tanks are mainly designed to treat sewage at a low cost via separation of solid and liquid fractions of the waste and passive AD of retained solids (Vymazal 2011). The liquid fraction is discharged to the environment after separation usually after 1–2 days of retention when a mixed gray and black water source is supplied. Retained solids will accumulate over time. Therefore, accumulated solids slowly reduce the effective volume of the tank, retention time of the liquid, and may increase the treatment efficiency (Singh et al. 2017).

Septic tanks demonstrate highly variable performance, high levels of contaminated and pathogenic effluent, and require high maintenance costs (Withers et al. 2014; Capodaglio et al. 2017). An estimated one out of four urban households in the United States (Kohler et al. 2016) and the majority of urban households in Europe and Southeast Asia use septic tanks with a system failure rate of approximately 20–80% (Speed et al. 2018).

In the areas where there are no centralized sewer systems, a septic tank is the on-site sanitation technology that is most commonly used to treat domestic wastewater. Septic tanks constructed in most developing countries do not perform satisfactorily due to improper design of the septic tanks such as size, configuration and hydraulic retention time (Polprasert et al. 2018). Beside this there is a limitation during operation as usually the septic tanks do not have leaching fields or drainage fields to further treat the septic tank effluent. Rather, septic tank effluent percolates into the surrounding soil or is discharged directly into nearby storm drains or waterways (Koottatep et al. 2014).

Due to the short residence time of septic tanks at about 1–3 days, septic tank effluent still contains high concentrations of organic matter, nutrients, and pathogenic microorganisms and is highly contaminated. Therefore, these septic tank effluents can cause contamination of surface and groundwater resources and nearby soils, ultimately resulting in water pollution and public health risks. Solar septic tanks (SSTs) are an emerging technology designed to improve the effluent quality by engineering the biology of septic systems and enhance solid decomposition (Polprasert et al. 2018).

SST is an innovative technology that uses AD at high temperatures of around 40–50 °C to reduce sludge accumulation in the septic tank (Figure 3). Compared with conventional septic tanks, high temperatures normally increase the methane-producing activity of microorganisms, which is generated in the sludge layer of the septic tank, and results in more organic matter decomposition, less total volatile solids or sludge accumulation, and higher methane (CH₄) production. The operation of SSTs with an elevated temperature of 40–50 °C may cause E. coli inactivity on 4–6 logs in the effluent. SSTs demonstrate increased
microbiological decomposition with increased degradation of organic matter, methane gas formation, and a 50% reduction of FS accumulation (Connelly et al. 2019).

It is a known fact that temperature promotes the death of pathogens, microbial activity and biodegradation of organic matter. Therefore, if a septic tank is operated at a higher temperature than the surrounding conditions, higher quality septic tank effluent should theoretically be obtained. Previous studies conducted on thermal treatment of wastewater have revealed that treating wastewater sludge at an elevated temperature of 60–80 °C have reduced the numbers of E. coli by 3.6–6 log within 30 minutes (Mocé-Llivina et al. 2019).

Different models have been used to validate the reduction rate of E. coli. The Weibull model \( \log N_t/N_0 = -\beta T^n \) \( \) (where \( N_t \) is the number of E. coli at time \( t \) (MPN/100 mL), \( N_0 \) is the initial number of E. coli (MPN/100 mL), \( \beta T^n \) is a temperature-dependent coefficient, \( n \) is the Weibull coefficient and \( \gamma \) is the regression factor, and this model appeared to be able to predict the inactivation efficiency of E. coli in a septic tank. Without heat treatment, the operation of septic tanks at ambient temperatures below about 30 °C can only achieve about 2 logs of E. coli inactivation, which may result in septic tank effluent that is unsafe for disposal or reuse (Koottatep et al. 2014).

SSTs operate with a central chamber, which is heated using a low-cost coil at a temperature of 50–60 °C through a passive solar heat collector. The solar septic tank design is illustrated in Figure 3. The circulating hot water is generated from the solar water heating device through heat transfer equipment, i.e. the copper coil, and this will increase the temperature inside the septic tank. The fecal pathogens could be effectively inactivated when the effluent passes through the disinfection chamber where the temperature could be more than 55 °C (Zhao et al. 2019). The temperature of the entire tank is then increased using the heat generated from the central chamber contributing to the increased microbial degradation of retained solids.

**ECONOMIC VIABILITY OF FECAL SLUDGE TREATMENTS**

At present, products of FS treatments are inefficiently used. FS is commonly buried and dumped into the environment. Sludge reuse is generally preferable over landfill because the marketing of treated sludge can generate income, and space used for landfill is lacking. The focus of research on FS is shifting from FS disposal to its reuse as fertilizer and soil conditioner. FS demonstrates lower chemical contaminants than sewage sludge; therefore, FS can be considered a valuable resource for recovery. If the treated FS has no market value and is not required for soil amendment, then it can be disposed of after proper treatment in an available sanitary landfill.

Development of viable market and business models along the FSM service chain can be started from the construction of the toilet to emptying, transportation, and reuse. To develop a market for treated sludge first the potential customers should be identified and analysis should be made based on their needs and wishes. The customer’s confidence should be developed by proving the benefits of the product in collaboration with an agricultural service or research institution.

The management of fecal sludge can only be successful in a sustainable way when it is financially ensured. Much attention should be made to find stable arrangements for covering running costs like salaries, operation, and maintenance of equipment and facilities. As far as possible, the running costs have to be recovered from the service fees or revenues. The treatment of FS in a circular economy can solve resource unavailabilities, such as the depletion
of nutrients in the soil, including phosphorus and nitrogen. It can also act as a point of reference in general waste management when the economic benefit of waste products encourages waste collection (Otoo et al. 2015).

If FS is properly managed and resources are recovered, then it can significantly provide key financial incentives and achieve a healthy and sanitary environment. Resource recovery from waste can help develop viable business models for sustainable sanitation solutions. Soil conditioning is a traditional form of resource recovery from FS solids. Some promising options for soil conditioning include the use of FS as building material components, protein source for animal feed, and industrial fuel (Krueger et al. 2020).

Recovering nutrients from FS is a way of returning nutrients to the soil to help control other sustainable development goals. For example, goal number two, target number three, aims to double the agricultural productivity of smallholder farmers by improving access to inputs and markets and subsequently achieve zero hunger (Trimmer et al. 2019). Target 15.3 addresses the fight against desertification and restores degraded land; therefore, the composted sewage sludge is made up of 50% organic matter for soil health rehabilitation. Nutrient recovery from FS is applied to the water, energy, and food and contributes to the simultaneous solution of problems related to water and food production (Bawiec et al. 2016).

The economic benefit of final products from FS can potentially increase the sustainability of FSM in low-income countries by compensating for a fraction of the cost of treatment and disposal. The potential market value of the same final product can vary significantly between countries. Therefore, the perception of the local community and the availability of markets must be considered because market attractiveness of the end product from FS is a crucial criterion along with many other challenges for selecting resource recovery technologies (Dodane et al. 2012).

LIMITATIONS AND CHALLENGES OF FECAL SLUDGE HYGIENIZATION

FS contains a high number of microorganisms that mostly originate from feces. These microorganisms can be pathogenic, and the impact of untreated FS is a significant risk to human health; therefore, it requires proper and adequate sanitization before reuse or disposal (Albihn & Vinnerås 2007; Winker et al. 2009). However, FS is commonly transported to a dump site or treatment plant directly after tank cleaning or disposed of in nearby excavated pits, drainage channels, natural ditches, streams, and other bodies of water in many developing countries.

FS is also used without additional treatment on agricultural land and discharged into fish ponds and lakes. These methods of excreta disposal are used mostly in urban residential areas of Africa, Asia, and Latin America (Toledo et al. 2019). Pathogens are classified into four categories, namely, bacteria, protozoa, helminths, and viruses. Table 2 lists some of the common pathogens that may be excreted in feces and their importance in disease transmission. Therefore, the selected treatment method of FS should be based on the end-use or disposal and handled hygienically. Many urban residents in developing countries (more than 90% in sub-Saharan Africa) do not have access to the sewerage or water supply necessary for its operation.

Only a fraction of the population living in the city center of developing countries has access to sewerage networks and wastewater treatment plants. By comparison, a higher percentage of the population uses septic tanks or pit latrines for collecting the sludge that will be disposed of in a dumping site by the private or public sector. Figure 3 shows the sanitation service chain of on-site sanitation technologies. Pit latrines require frequent emptying; otherwise, FS from the pit can overflow and contaminate the surrounding environment (Nyakeri et al. 2017). This mainly happens to people with insufficient income for emptying services and instead unload the sludge with buckets using their hands with minimal protection. Another sanitation challenge is the poor or even absence of appropriate landfill site layout for FS treatment that leads to the leakage of FS into the surrounding environment. Moreover, the design of pit latrines must be considered depending on the volume capacity of pits because they can fill rapidly. New research is increasingly shifting toward a comprehensive approach by examining new sanitation facility designs or using existing treatment technologies for sludge disinfection (Lalander et al. 2013a, 2013b).
In summary, onsite treatment technologies serve the sanitation needs of 2.7 billion people worldwide; however, the world population is expected to grow to over five billion by the year 2030. While the sanitation needs of many urban dwellers in low- and middle-income countries are generally met by on-site technologies, a general management system for the subsequent collection, transportation, treatment, and use/disposal of FS does not yet exist. On-site technologies have traditionally been considered a temporary solution until permanent sewerage systems can be built. However, the development of a standard functioning sewer network cannot keep up with the pace of urban expansion, especially in low-income cities.

In urban areas of developing countries, only a small percentage of people, mainly those living in city centers, are connected to sewerage networks or sewage treatment plants. A higher percentage of people connected to septic tanks or pit latrines have to have their sludge removed by private or public contractors. Once the sludge is removed the waste is then filled into a damping site. However, in developing countries, the septic tanks do not perform satisfactorily mainly due to the lack of improper design (such as configuration, sizing, and hydraulic retention time) and the limitations on operation including the absence of post-treatments and leaching fields.

**CONCLUSIONS**

The introduction of treatment technologies for FSM significantly reduces the number of open defecation practices. However, appropriate FSM funding is required for operation and maintenance activities of long-term functionality to avoid the crisis in sludge management and negative effects on human health and the environment. Technologies applied in the field may offer feasible and affordable options if the entire service chain, including collection, transportation, processing, and safe disposal, is properly managed.
Therefore, untreated FS will end up directly in surrounding areas, contaminate the environment with pathogens, and severely affect public health if an appropriate FSM structure is lacking. Awareness of common challenges associated with resource recovery and ensuring the proper protection of human health and the environment must be addressed. Therefore, fully understanding key factors in selecting suitable and feasible options of treatment technologies is required to recover resources from FS potentially. Human excreta can play a crucial role in poverty alleviation by increasing soil fertility, enhancing agricultural food production, and using feces for soil amendment.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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