Review Paper

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

Abraham Amenay Zewde, Zifu Li and Zhou Xiaoqin

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

Abraham Amenay Zewde (corresponding author)
Zifu Li
Zhou Xiaoqin
School of Energy and Environmental Engineering,
Beijing Key Laboratory of Resource-Oriented Treatment of Industrial Pollutants,
University of Science and Technology,
Beijing Xueyuan 30, Beijing 10003,
China
E-mail: *aaz4ev@gmail.com*

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.

---

doi: 10.2166/washdev.2021.268

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 (Lalander *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.

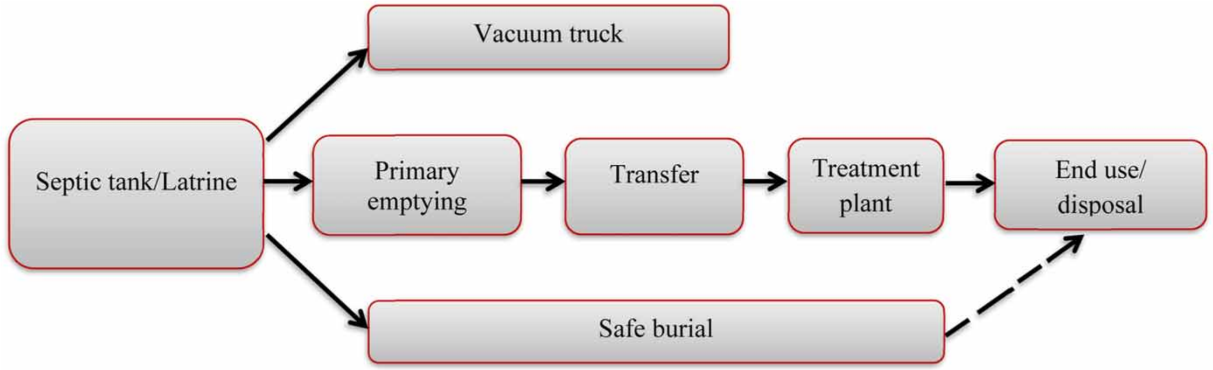

Figure 1 | Sanitation service chain of on-site sanitation technologies.

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

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

The use of pathogen inactivating action of uncharged ammonia (NH_3) 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 (NH_4+), 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 flash 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 (NH_3) 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 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 cerevisia*e or lactic acid fermentation with a broad range of bacteria called lactic acid bacteria (LAB) (Papadimitriou *et al.* 2015). 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.* 2001; Maya *et al.* 2019). Lime is easy to apply and also provides an alkaline environment, which is hostile to biological activity

(Anderson *et al.* 2015). 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.* 2001). The inactivation of helminth eggs is highly dependent on the storage life of lime-treated sludge (Foote *et al.* 2017).

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).

Figure 2 | Powdered lime which can be used to treat fecal sludge.

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 (CH_4) 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

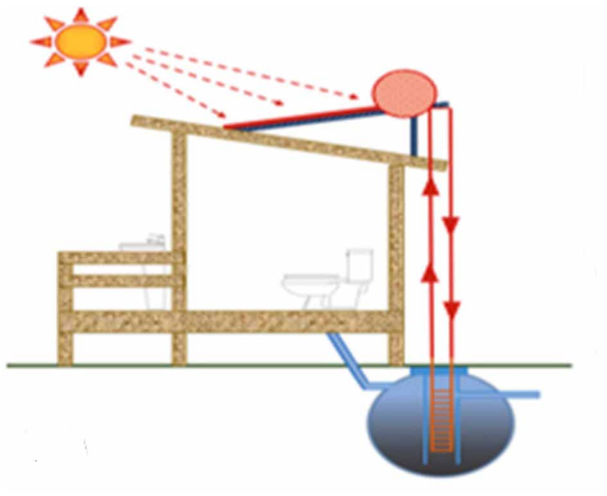

Figure 3 | Schematic illustration of Solar Septic Tank (SST) in a field site.

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.* 2003).

Different models have been used to validate the reduction rate of *E. coli*. The Weibull model ($\log N_t/N_0 = \_\gamma b_T t^n$), where Nt is the number of *E. coli* at time t (MPN/100 mL), N_0 is the initial number of *E. coli* (MPN/100 mL), bT is a temperature-dependent coefficient, n is the Weibull coefficient and γ 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).

Table 2 | Selected pathogens that may be excreted in faeces and related disease symptoms (Stenström 2004)

Group	Pathogen	Disease symptoms
Bacteria	Aeromonas spp.	Enteritis
	Campylobacter jejuni/coli	Campylobacteriosis – diarrhea, cramping, abdominal pain, fever, nausea, arthritis, Guillain-Barré syndrome
	Escherichia coli (EIEC, EPEC, ETEC, EHEC)	Enteritis. For EHEC there are also internal hemorrhages
	Salmonella typhi/paratyphi	Typhoid, headache, fever, malaise, anorexia, cough
	Salmonella spp	Salmonellosis – diarrhea, and abdominal cramps
	Shigella spp.	Shigellosis – dysentery (bloody diarrhea), vomiting, cramps, fever; Reiters syndrome
	Vibrio cholera	Cholera – watery diarrhea
Virus	Adenovirus	Various; respiratory illness, here added due to enteric *types*
	Enteric adenovirus types 40 and 41	Enteritis
	Enterovirus types 68–71	Meningitis; encephalitis; paralysis
	Hepatitis A	Hepatitis – fever, malaise, anorexia, abdominal discomfort, jaundice
	Hepatitis E	Hepatitis
	Poliovirus	Poliomyelitis – fever, nausea, vomiting, headache, paralysis
	Rotavirus	Enteritis
Parasitic protozoa	*Cryptosporidium parvum*	Cryptosporidiosis – watery diarrhea, abdominal cramps and pain
	Cyclospora histolytica	Often asymptomatic; diarrhea; abdominal pain
	Entamoeba histolytica	Amoebiasis – often asymptomatic, dysentery, abdominal discomfort, fever, chills
	Giardia intestinalis	Giardiasis – diarrhea, abdominal cramps, malaise, weight loss
Helminths	*Ascaris lumbricoides*	No or few symptoms; wheezing; coughing; enteritis; pulmonary eosinophilia
	Taenia solium/saginata	Taeniasis
	Trichuris trichura	Trichuriasis – Unapparent through to vague digestive tract distress to emaciation with dry skin and diarrhea
	Hookworm	Itch; rash; cough; anemia; protein deficiency
	Schistosoma spp. (blood fluke)	Schistosomiasis, bilharzias

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.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the project support of the National Key Research and Development Plan (2019YFC0408700), and the Fundamental Research Funds for the Central Universities (FRF-DF-19-001).

DATA AVAILABILITY STATEMENT

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

REFERENCES

Abdoli, A. & Maspi, N. 2018 Commentary: estimates of global, regional, and national morbidity, mortality, and aetiologies of diarrhoeal diseases: a systematic analysis for the global burden of disease study 2015. *Frontiers in Medicine* **Supl. 5**, 1211–1228. doi: 10.3389/fmed.2018.00011. (Epub ahead of print).

Albihn, A. & Vinnerås, B. 2007 Biosecurity and arable use of manure and biowaste – treatment alternatives. *Livestock Science* **112** (Suppl. 3), 232–239.

Anderson, C., Malambo, D. H., Perez, M. E. G., Nobela, H. N., DePooter, L., Spit, J., Hooijmans, C. M., De Vossenberg, J. V., Greya, W., Thole, B. & Van, L. 2015 Lactic acid fermentation, urea and lime addition: promising faecal sludge sanitizing methods for emergency sanitation. *International Journal of Environmental Research and Public Health* **12** (Suppl. 11), 13871–13885.

Andreev, N., Ronteltap, M., Boincean, B. & Lens, P. N. 2018 Lactic acid fermentation of human excreta for agricultural application. *Journal of Environmental Management* **206**, 890–900.

Baggi, F., Demarta, A. & Peduzzi, R. 2001 Persistence of viral pathogens and bacteriophages during sewage treatment: lack of correlation with indicator bacteria. *Research in Microbiology* **152** (Suppl. 8), 743–751.

Bawiec, A., Pawęska, K. & Jarząb, A. 2016 Changes in the microbial composition of municipal wastewater treated in biological processes. *Journal of Ecological Engineering* **17** (Suppl. 3), 41–46.

Berendes, D. M., Sumner, T. A. & Brown, J. M. 2017 Safely managed sanitation for all means fecal sludge management for at least 1.8 billion people in low and middle income countries. *Environmental Science & Technology* **51** (Suppl. 5), 3074–3083.

Borja-Vega, C., Morales, E. E. G. & Gonzalez, J. A. 2019 Incidence of subsidies in residential public services in Mexico: the case of the water sector. *Water* **11** (Suppl. 10), 2078.

Capodaglio, A. G., Callegari, A., Cecconet, D. & Molognoni, D. 2017 Sustainability of decentralized wastewater treatment technologies. *Water Practice and Technology* **12** (Suppl. 2), 463–477.

Cardeña, R., Valdez-Vazquez, I. & Buitrón, G. 2017 Effect of volatile fatty acids mixtures on the simultaneous photofermentative production of hydrogen and polyhydroxybutyrate. *Bioprocess and Biosystems Engineering* **40** (Suppl. 2), 231–239.

Chávez, J. A., Mora-Ramírez, M. A., Almiray-Pinzón, R. C., Pérez-Avilés, R., Díaz-Cabrera, E., Alcántara-Flores, J. L. & Patiño-Iglesias, M. E. 2019 Vegetative growth response of beets and lettuce to stored human urine. *Agronomy Research* **17** (Suppl 6), 2220–2232.

Christiaens, M. E., Gildemyn, S., Matassa, S., Ysebaert, T., De Vrieze, J. & Rabaey, K. 2017 Electrochemical ammonia recovery from source-separated urine for microbial protein production. *Environmental Science and Technology* **51** (Suppl. 22), 13143–13150.

Connelly, S., Pussayanavin, T., Randle-Boggis, R. J., Wicheansan, A., Jampathong, S., Keating, C., Ijaz, U. Z., Sloan, W. T. & Koottatep, T. 2019 Solar septic tank: next generation sequencing reveals effluent microbial community composition as a useful index of system performance. *Water* **11** (Suppl. 12), 2660.

Dangol, B. 2013 *Faecal Sludge Characterization and co-Treatment with Municipal Wastewater: Process and Modeling Considerations*. UNESCO-IHE Institute for Water Education, Delft, The Netherlands, pp. 38–57.

Dias, E., Ebdon, J. & Taylor, H. 2018 The application of bacteriophages as novel indicators of viral pathogens in wastewater treatment systems. *Water Research* **129**, 172–179.

Ding, S., Meale, S. J., Alazzeh, A. Y., He, M. L., Ribeiro, G. O., Jin, L., Wang, Y., Dugan, M. E. R., Chaves, A. V. & McAllister, T. A. 2017 Effect of *Propionibacterium freudenreichii* in diets containing rapeseed or flaxseed oil on *in vitro* ruminal fermentation, methane production and fatty acid biohydrogenation. *Animal Production Science* **57** (Suppl. 10), 2051–2059.

Dodane, P. H., Mbéguéré, M., Sow, O. & Strande, L. 2012 Capital and operating costs of full-scale fecal sludge management and wastewater treatment systems in Dakar, Senegal. *Environmental Science & Technology* **46** (Suppl. 7), 3705–3711.

Dongzagla, A., Jewitt, S. & O'Hara, S. 2021 Seasonality in faecal contamination of drinking water sources in the Jirapa and Kassena-Nankana Municipalities of Ghana. *Science of the Total Environment* **752**, 141846.

Ercumen, A., Pickering, A. J., Kwong, L. H., Arnold, B. F., Parvez, S. M., Alam, M., Sen, D., Islam, S., Kullmann, C., Chase, C. & Ahmed, R. 2017 Animal feces contribute to domestic fecal contamination: evidence from *E. coli* measured in water, hands, food, flies, and soil in Bangladesh. *Environmental Science & Technology* **51** (Suppl. 15), 8725–8734.

Factura, H., Yemaneh, A., Bulbo, M., Buzie, C., Gensch, R. & Otterpohl, R. 2011 Lactic acid fermentation of urine and faeces through Terra Preta Sanitation. In *Poster Presented at: the Conference on Decentralized Wastewater Treatment Systems (DEWATS) for Urban Environments in Asia*, Vol. 75.

Favas, P. J. C., Sarkar, S. K., Rakshit, D., Venkatachalam, P. & Prasad, M. N. V. 2016 Acid mine drainages from abandoned mines: hydrochemistry, environmental impact, resource recovery, and prevention of pollution. In: *Environmental Materials and Waste* (M. N. V. Prasad & S. B. T. Kaimin eds). Academic Press, Cambridge, pp. 413–462.

Foote, A. M., Woods, E., Fredes, F. & Leon, J. S. 2017 Rendering fecal waste safe for reuse via a cost-effective solar concentrator. *Journal of Water, Sanitation and Hygiene for Development* **7** (Suppl. 2), 252–259.

Forbis-Stokes, A. A., O'Meara, P. F., Mugo, W., Simiyu, G. M. & Deshusses, M. A. 2016 Special issue: innovative global solutions for bioenergy production. *Environmental Engineering Science* **33** (Suppl. 11), 898–906.

Furlong, C., Rajapaksha, N. S., Butt, K. R. & Gibson, W. T. 2017 Is composting worm availability the main barrier to large-scale adoption of worm-based organic waste processing technologies? *Journal of Cleaner Production* **164**, 1026–1033.

Gao, M., Zhang, L., Florentino, A. P. & Liu, Y. 2019 Performance of anaerobic treatment of blackwater collected from different toilet flushing systems: can we achieve both energy recovery and water conservation? *Journal of Hazardous Materials* **365**, 44–52.

Gijzen, H. 2001 Anaerobes, aerobes and phototrophs (A winning team for wastewater management). *Water Science and Technology* **44** (Suppl. 8), 123–132.

Gorbalenya, A. E., Baker, S., Baric, R., de Groot, R., Drosten, C., Gulyaeva, A. A., Haagmans, B. L., Lauber, C., Leontovich, A. M., Neuman, B. W., Penzar, D., Perlman, S., Poon, L. L. M., Samborskiy, D. V., Sidorov, I., Solar, I. & Ziebuhr, J. 2020 The species severe acute respiratory syndrome related coronavirus: classifying 2019-nCoV and naming it SARS-CoV-2. *Nature Microbiology* **5**, 536–544.

Greya, W., Thole, B., Anderson, C., Kamwani, F., Spit, J. & Mamani, G. 2016 Off-site lime stabilisation as an option to treat pit latrine faecal sludge for emergency and existing on-site sanitation systems. *Journal of Waste Management* **2016**, 1–8.

Gyawali, P. 2018 Infectious helminth ova in wastewater and sludge: a review on public health issues and current quantification practices. *Water Science and Technology* **77** (Suppl. 4), 1048–1061.

Harroff, L. A., Liotta, J. L., Bowman, D. D. & Angenent, L. T. 2019 Current time-temperature relationships for thermal inactivation of Ascaris eggs at mesophilic temperatures are too conservative and may hamper development of simple, but effective sanitation. *Water Research* **5**, 100036.

Hawkins, B. T., Sellgren, K. L., Cellini, E., Klem, E. J., Rogers, T., Lynch, B. J., Piascik, J. R. & Stoner, B. R. 2019 Remediation of suspended solids and turbidity by improved settling tank design in a small-scale, free-standing toilet system using recycled blackwater. *Water and Environment Journal* **33** (Suppl. 1), 61–66.

Hellmér, M., Paxéus, N., Magnius, L., Enache, L., Arnholm, B., Johansson, A., Bergström, T. & Norder, H. 2014 Detection of pathogenic viruses in sewage provided early warnings of hepatitis A virus and norovirus outbreaks. *Applied and Environmental Microbiology* **80** (Suppl. 21), 6771–6781.

Hewitt, J., Leonard, M., Greening, G., Lewis, E. & Gillian, D. 2011 Influence of wastewater treatment process and the population size on human virus profiles in wastewater. *Water Research* **45** (18), 6267–6276. https://doi.org/10.1016/j.watres.2011.09.029.

Hill, G. B., Baldwin, S. A. & Vinnerås, B. 2013 Composting toilets a misnomer: excessive ammonia from urine inhibits microbial activity yet is insufficient in sanitizing the end-product. *Journal of Environmental Management* **119**, 29–35.

Hu, Y., Cheng, H. & Tao, S. 2017 Environmental and human health challenges of industrial livestock and poultry farming in China and their mitigation. *Environment International* **107**, 111–130.

Jamal, A., Norieh, N. & Farzadkia, M. 2018 Comparison of aerobic and lime stabilization methods for evaluation of sewage sludge reuse. *Journal of Environmental Science and Technology* **4** (Suppl. 2), 182–190.

Jara-Samaniego, J., Pérez-Murcia, M. D., Bustamante, M. A., Pérez-Espinosa, A., Paredes, C., López, M., López-Lluch, D. B., Gavilanes-Terán, I. & Moral, R. 2017 Composting as sustainable strategy for municipal solid waste management in the Chimborazo Region, Ecuador: Suitability of the obtained composts for seedling production. *Journal of Cleaner Production* **141**, 1349–1358.

Kania, M., Gautier, M., Imig, A., Michel, P. & Gourdon, R. 2019 Comparative characterization of surface sludge deposits from fourteen French Vertical Flow Constructed Wetlands sewage treatment plants using biological, chemical and thermal indices. *Science of the Total Environment* **647**, 464–473.

Karunanithi, R., Szogi, A., Bolan, N. S., Naidu, R., Ok, Y. S., Krishnamurthy, S. & Seshadri, B. 2016 Phosphorus recovery from wastes. In: *Environmental Materials and Waste: Resource Recovery and Pollution Prevention* (M. N. V. Prasad & S. B. T. Kaimin eds). Academic Press, Cambridge, pp. 687–705.

Katukiza, A. Y., Ronteltap, M., Niwagaba, C. B., Foppen, J. W. A., Kansiime, F. P. N. L. & Lens, P. N. L. 2012 Sustainable sanitation technology options for urban slums. *Biotechnology Advances* **30** (Suppl 5), 964–978.

Kimetu, J. M., Mugendi, D. N., Palm, C. A., Mutuo, P. K., Gachengo, C. N., Bationo, A., Nandwa, S. & Kungu, J. B. 2004 Nitrogen fertilizer equivalencies of organics of differing quality and optimum combination with inorganic nitrogen source in Central Kenya. *Nutrient Cycling in Agroecosystems* **68** (Suppl 2), 127–135.

Kohler, L. E., Silverstein, J. & Rajagopalan, B. 2016 Predicting life cycle failures of on-site wastewater treatment systems using generalized additive models. *Environmental Engineering Science* **33** (Suppl. 2), 112–124.

Koottatep, T., Phuphisith, S., Pussayanavin, T., Panuvatvanich, A. & Polprasert, C. 2014 Modeling of pathogen inactivation in thermal septic tanks. *Journal of Water Sanitation and Hygiene for Development* **4** (Suppl. 1), 81–88.

Krueger, B. C., Fowler, G. D., Templeton, M. R. & Moya, B. 2020 Resource recovery and biochar characteristics from full-scale faecal sludge treatment and co-treatment with agricultural waste. *Water Research* **169**, 115253.

Lalander, C., Diener, S., Magri, M. E., Zurbrügg, C., Lindström, A. & Vinnerås, B. 2013a Faecal sludge management with the larvae of the black soldier fly (Hermetia illucens) – from a hygiene aspect. *Science of the Total Environment* **458**, 312–318.

Lalander, C. H., Hill, G. B. & Vinnerås, B. 2013b Hygienic quality of faeces treated in urine diverting vermicomposting toilets. *Waste Management* **33**, 2204–2210.

Li, M., Xia, T., Zhu, C., Xi, B., Jia, X., Wei, Z. & Zhu, J. 2014 Effect of short-time hydrothermal pretreatment of kitchen waste on biohydrogen production: fluorescence spectroscopy coupled with parallel factor analysis. *Bioresource Technology* **172**, 382–390.

Lindberg, E. & Rost, A. 2018 *Treatment of Faecal Sludge From pit Latrines and Septic Tanks Using Lime and Urea: Pathogen die-off with Respect to Time of Storage*, p. 48. Available from: https://ltu.diva-portal.org/smash/get/diva2:1242729/FULLTEXT01.pdf.

Liu, H. T. 2016 Achilles heel of environmental risk from recycling of sludge to soil as amendment: a summary in recent ten years (2007–2016). *Waste Management* **56**, 575–583.

Liu, H., Ji, H. F., Zhang, D. Y., Wang, S. X., Wang, J., Shan, D. C. & Wang, Y. M. 2015 Effects of Lactobacillus brevis preparation on growth performance, fecal microflora and serum profile in weaned pigs. *Livestock Science* **178**, 251–254.

Lohman, H. A., Trimmer, J. T., Katende, D., Mubasira, M., Nagirinya, M., Nsereko, F., Banadda, N., Cusick, R. D. & Guest, J. S. 2020 Advancing sustainable sanitation and agriculture through investments in human-derived nutrient systems. *Environmental Science and Technology* **54** (Suppl. 15), 9217–9227.

Mara, D. 2013 Pits, pipes, ponds and me. *Water Research* **47**, 2105–2117.

Mawioo, P. M., Hooijmans, C. M., Garcia, H. A. & Brdjanovic, D. 2016 Microwave treatment of faecal sludge from intensively used toilets in the slums of Nairobi, Kenya. *Journal of Environmental Management* **184**, 575–584.

Maya, C., Pérez, M., Velásquez, G., Barrios, J. A., Román, A. & Jiménez, B. 2019 Quick incubation process to determine inactivation of Ascaris and Toxocara eggs. *Water Science and Technology* **80** (Suppl. 12), 2328–2337.

Meale, S. J., Chaves, A. V., He, M. L., Guan, L. L. & McAllister, T. A. 2015 Effects of various dietary lipid additives on lamb performance, carcass characteristics, adipose tissue fatty acid composition, and wool characteristics. *Journal of Animal Science* **93** (Suppl. 6), 3110–3120.

Mengjiao, G., Lei, Z., Florentino, A. B. & Yang, L. 2019 Performance of anaerobic treatment of black water collected from different toilet flushing systems: Can we achieve both energy recovery and water conservation? *J. Hazard. Mater.* **365**, 44–52.

Mignotte-Cadiergues, B., Maul, A., Huyard, A., Capizzi, S. & Schwartzbrod, L. 2001 The effect of liming on the microbiological quality of urban sludge. *Water Science and Technology* **43** (Suppl. 12), 195–200.

Mocé-Llivina, L., Muniesa, M., Pimenta-Vale, H., Lucena, F. & Jofre, J. 2003 Survival of bacterial indicator species and bacteriophages after thermal treatment of sludge and sewage. *Applied and Environmental Microbiology* **69** (Suppl. 3), 1452–1456.

Mozzi, F., Ortiz, M. E., Bleckwedel, J., De Vuyst, L. & Pescuma, M. 2013 Metabolomics as a tool for the comprehensive understanding of fermented and functional foods with lactic acid bacteria. *Food Research International* **54** (Suppl. 1), 1152–1161.

Nagy, J. & Zseni, A. 2017 Human urine as an efficient fertilizer product in agriculture. *Agronomy Research* **15** (Suppl. 2), 490–500.

Nordin, A., Nyberg, K. & Vinneras, B. 2009 Inactivation of Ascaris Eggs in source-separated urine and feces by ammonia at ambient temperatures. *Applied and Environmental Microbiology* **75** (Suppl. 3), 662–667.

Nyakeri, E. M., Ogola, H. J., Ayieko, M. A. & Amimo, F. A. 2017 An open system for farming black soldier fly larvae as a source of proteins for smallscale poultry and fish production. *Journal of Insects as Food and Feed* **3** (Suppl. 1), 51–56.

Otoo, M., Drechsel, P. & Hanjra, M. A. 2015 Business models and economic approaches for nutrient recovery from wastewater and fecal sludge. In: *Wastewater* (P. Drechsel, M. Qadir & D. Wichelns eds). Springer, Dordrecht, pp. 247–268.

Papadimitriou, K., Pot, B. & Tsakalidou, E. 2015 How microbes adapt to a diversity of food niches. *Current Opinion in Food Science* **2**, 29–35.

Park, G. W. & Diez-Gonzalez, F. 2003 Utilization of carbonate and ammonia-based treatments to eliminate Escherichia coli o157: H7 and Salmonella Typhimurium DT104 from cattle manure. *Journal of Applied Microbiology* **94** (Suppl. 4), 675–685.

Peal, A., Evans, B., Blackett, I., Hawkins, P. & Heymans, C. 2014 Fecal sludge management: a comparative analysis of 12 cities. *Journal of Water Sanitation and Hygiene for Development* **4** (Suppl. 4), 563–575.

Polprasert, C., Koottatep, T. & Pussayanavin, T. 2018 Solar septic tanks: a new sanitation paradigm for Thailand 4.0. *Science Asia* **44**, 39–43.

Rashed, M. Y. A. & Hithnawi, T. M. 2006 Domestic septage characteristics and cotreatment impacts on Albireh wastewater treatment plant efficiency. *Dirasat: Engineering Sciences* **33** (Suppl. 2), 187–197.

Rehrah, D., Bansode, R. R., Hassan, O. & Ahmedna, M. 2016 Physico-chemical characterization of biochars from solid municipal waste for use in soil amendment. *Journal of Analytical and Applied Pyrolysis* **118**, 42–53.

Saa, D. L. T., Nissen, L. & Gianotti, A. 2019 Metabolomic approach to study the impact of flour type and fermentation process on volatile profile of bakery products. *Food Research International* **119**, 510–516.

Schüch, A., Morscheck, G. & Nelles, M. 2019 Technological options for biogenic waste and residues – overview of current solutions and developments. In: *Waste Valorisation and Recycling* (S. Ghosh ed.). Springer, Singapore, pp. 307–322.

Scott, R. E., Ross, I., Hawkins, P., Blackett, I. & Smith, M. D. 2019 Diagnostics for assessing city-wide sanitation services. *Journal of Water Sanitation and Hygiene for Development* **9** (Suppl. 1), 111–118.

Seol, K. H., Yoo, J., Yun, J., Oh, M. H. & Ham, J. S. 2019 Inhibitory activity of lactic acid bacteria against fungal spoilage. *Journal of Milk Science Biotechnology* **37** (Suppl. 2), 83–93.

Silva, D. A. L., Lahr, F. A. R., Varanda, L. D., Christoforo, A. L. & Ometto, A. R. 2015 Environmental performance assessment of the melamine-urea-formaldehyde (MUF) resin manufacture: a case study in Brazil. *Journal of Cleaner Production* **96**, 299–307.

Simmons, F. J. & Xagoraraki, I. 2011 Release of infectious human enteric viruses by full-scale wastewater utilities. *Water Research* **45** (Suppl. 12), 3590–3598.

Singh, S., Mohan, R. R., Rathi, S. & Raju, N. J. 2017 Technology options for faecal sludge management in developing countries: benefits and revenue from reuse. *Environmental Technology and Innovation* **7**, 203–218.

Sowale, A., Anthony, E. J. & Kolios, A. J. 2019 Optimisation of a quasi-steady model of a free-piston stirling engine. *Energies* **12** (Suppl. 1), 72.

Speed, C. D., Fretwell, B. A. & Davison, P. S. 2018 The role of septic tanks in the dissolved phosphorus budget of the Upper River Nar and possible implications for other catchments. *Quarterly Journal of Engineering Geology and Hydrogeology* **52** (Suppl. 1), 23–37.

Stenström, T. A. 2004 *Guidelines on the Safe Use of Urine and Faeces in Ecological Sanitation Systems*. EcoSanRes Programme, Stockholm Environmental Institute, Stockholm.

Strande, L. 2014 Faecal waste: the next sanitation challenge. *Water* **21**, 16–18.

Tao, Y., Hu, X., Zhu, X., Jin, H., Xu, Z., Tang, Q. & Li, X. 2016 Production of butyrate from lactate by a newly isolated Clostridium sp. BPY5. *Applied Biochemistry and Biotechnology* **179** (Suppl. 3), 361–374.

Toledo, M., Márquez, P., Siles, J. A., Chica, A. F. & Martín, M. A. 2019 Co-composting of sewage sludge and eggplant waste at full scale: feasibility study to valorize eggplant waste and minimize the odoriferous impact of sewage sludge. *Journal of Environmental Management* **247**, 205–213.

Torgbo, S., Quaye, E. A., Adongo, T. A. & Opoku, N. 2018 The effects of dried faecal sludge and municipal waste co-compost on microbial load and yield of cabbage (Brassica oleracea L. Var. capitata) and lettuce (Lactuca sativa). *Journal of Microbiology, Biotechnology and Food Sciences* **7** (Suppl. 6), 555–561.

Tremonte, P., Pannella, G., Succi, M., Tipaldi, L., Sturchio, M., Coppola, R., Luongo, D. & Sorrentino, E. 2017 Antimicrobial activity of Lactobacillus plantarum strains isolated from different environments: a preliminary study. *International Food Research Journal* **24** (Suppl. 2), 852–859.

Trimmer, J. T., Margenot, A. J., Cusick, R. D. & Guest, J. S. 2019 Aligning product chemistry and soil context for agronomic reuse of human-derived resources. *Environmental Science & Technology* **53** (Suppl. 11), 6501–6510.

Van Asperen, I. A., Medema, G., Borgdorff, M. W., Sprenger, M. J. & Havelaar, A. H. 1998 Risk of gastroenteritis among triathletes in relation to faecal pollution of fresh waters. *International Journal of Epidemiology* **27** (Suppl. 2), 309–315.

Vymazal, J. 2011 Constructed wetlands for wastewater treatment: five decades of experience. *Environmental Science & Technology* **45** (Suppl. 1), 61–69.

Wang, J., Gao, M., Wang, Q., Zhang, W. & Shirai, Y. 2016 Pilot-scale open fermentation of food waste to produce lactic acid without inoculum addition. *RSC Advances* **6** (Suppl. 106), 104354–104358.

WHO 2006 *WHO Guidelines for the Safe Use of Wasterwater Excreta and Greywater, Vol. 1*. World Health Organization, Geneva.

WHO 2014 *Progress on Drinking Water and Sanitation*. World Health Organization, Geneva, pp. 80–80.

WHO 2018 *Guidelines on Sanitation and Health*. World Health Organization, Geneva. Available from: http://www.who.int/water_sanitation_health/publications/guidelines-on-sanitation-and-health/en/.

Winker, M., Vinnerås, B., Muskolus, A., Arnold, U. & Clemens, J. 2009 Fertiliser products from new sanitation systems: their potential values and risks. *Bioresource Technology* **100** (Suppl. 18), 4090–4096.

Withers, P. J., Jordan, P., May, L., Jarvie, H. P. & Deal, N. E. 2014 Do septic tank systems pose a hidden threat to water quality? *Frontiers in Ecology and the Environment* **12** (Suppl. 2), 123–130.

Wong, J. W. C., Wang, X. & Selvam, A. 2017 Improving compost quality by controlling nitrogen loss during composting. In: *Current Developments in Biotechnology and Bioengineering* (C. Larroche, M. Sanroman, G. Du & A. Pandey eds). Elsevier, Oxford, pp. 59–82.

Yermán, L., Hadden, R. M., Carrascal, J., Fabris, I., Cormier, D., Torero, J. L., Gerhard, J. I., Krajcovic, M., Pironi, P. & Cheng, Y. L. 2015 Smouldering combustion as a treatment technology for faeces: exploring the parameter space. *Fuel* **147**, 108–116.

Zakaria, F., Thye, Y. P., Hooijmans, C. M., Garcia, H. A., Spiegel, A. D. & Brdjanovic, D. 2017 User acceptance of the eSOS ® Smart Toilet in a temporary settlement in the Philippines. *Water Practice & Technology* **12** (Suppl. 4), 832–847.

Zhao, J., Li, Y., Pan, S., Tu, Q. & Zhu, H. 2019 Performance of a forward osmotic membrane bioreactor for anaerobic digestion of waste sludge with increasing solid concentration. *Journal of Environmental Management* **246**, 239–246.

First received 16 December 2020; accepted in revised form 28 February 2021. Available online 2 April 2021