1-1-2022

In Situ Treatment Technologies for Pit Latrines to Mitigate Groundwater Contamination by Fecal Pathogens: A Review of Recent Technical Advances

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Journal of
Water, Sanitation & Hygiene for Development

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Review Paper

In situ treatment technologies for pit latrines to mitigate groundwater contamination by fecal pathogens: a review of recent technical advances

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ABSTRACT

On-site sanitation systems such as pit latrines are extensively used around the world, while there is a growing number of evidence documenting the impact of pit latrines on groundwater quality that may affect human health. Hence, this paper summarizes the various safe-sanitation technologies by broadly categorizing them into fecal pathogen disinfection methods (anaerobic digestion, chemical disinfection, biological additives, solar pasteurization and vermicomposting) and capturing methods (pit lining and permeable reactive barriers, the latter of which simultaneously capture and sanitize fecal sludge in pit latrines). While some of the reviewed technologies have been widely practiced for mitigating microbial contamination of the groundwater, others are still in the early stage of commercialization and field validation. Though there are challenges to the selection and adoption of the most appropriate technology, this paper discusses the readiness of each technology as a stand-alone fecal sludge management solution.

Key words: fecal pathogen, groundwater contamination, pit latrine, pit lining, sludge treatment

HIGHLIGHTS

- Pit latrines impact groundwater quality that may affect human health.
- Low-cost treatment techniques are discussed to capture and treat pathogens in pit latrines.
- Pit liners such as peat, clay, hydrophobic membranes and permeable reactive barriers help capture pathogens.
- When compared with other methods, the chemical disinfection method with chlorine, lime, Ikati and Soda ranked best with the highest score.

INTRODUCTION

In 2015, the United Nations included the following Sustainable Development Goals (SDGs) on achieving universal and equitable access to safe water and adequate sanitation and hygiene by 2030 (UN General Assembly 2015). In 2017, 90% of the world population used at least basic drinking water services with >71% of the population using safely managed services (UNICEF & WHO 2019a). Unfortunately, only 45% of the total population uses safely managed sanitation services (WHO 2018a). Mara & Evans (2018) estimate that it would require four times the number who received improved sanitation per day during the 15-year period from 2001 to 2015 to be served with safely managed sanitation to achieve the SDG for sanitation by the 2030 deadline. Mara (2012) noted that the real problem here lies with the governments' lack of commitment to sanitation despite advocacy programs such as the International Water Supply and Sanitation Decade (1981–1990), Safe Water 2000 (1991–2000) and the Millennium Development Goals (MDGs) (2001–2015).

The World Health Organization (WHO) reports that infectious diseases highly associated with unsafe water and inadequate sanitation are a major cause of death and disease annually in both low- and middle-income countries, especially among children <5 years of age (Mills & Cumming 2016). These consist of diarrheal diseases (including cholera, salmonellosis, shigellosis, amoebiasis, and other bacterial, protozoal and viral intestinal diseases), schistosomiasis, trachoma and the nematode infections (ascariasis, trichuriasis and hookworm disease) termed together as DSTN diseases (Franceys *et al.* 1992;

Kerridge *et al.* 2013). In 2016 alone, 55% of all DSTN deaths in the world (age 0–4 years = 481,809; all ages = 1,420,107) were reported in the following five countries only: India, Nigeria, Pakistan, Democratic Republic of Congo (DRC) and Ethiopia (Table 1) (WHO 2018b). Av & Sharma (2019) provide significant evidence for nutritional deficiency, stunting, underweight issues and impaired immune function in children aged <5 years related to DSTN diseases resulting from a lack of sanitation or open defecation (OD). Total intestinal nematode infections account for <1% of all DSTN deaths; however, they can contribute significantly to malnutrition and suffering (Kerridge *et al.* 2013).

In DRC and Ethiopia, <45% of the population use at least basic drinking water services, while the number is much higher in Nigeria (71%), Pakistan (91%) and India (93%) (WHO & UNICEF 2019b). The data, summarized in Table 2, show that in the latter three countries >50% of the households still depended on groundwater sources for drinking water, while a large number of households use pit latrines (12–31%) for their sanitation needs or are forced to defecate in the open (10–30%). The perils of OD are well documented and there is now overwhelming evidence showing the impact of pit latrines on groundwater quality that may affect human health (Dzwairo *et al.* 2006; Graham & Polizzotto 2013; Orner *et al.* 2018). This has caused the SDGs to target and monitor the population using safely managed sanitation in addition to the number of improved sanitation facilities. By definition, a safe-sanitation option must ensure the safe collection, storage, sanitization and stabilization of fecal sludge.

Sanitization of fecal sludge is the appropriate pathogen reduction technique that ensures the safe handling, disposal and reuse of the treatment and effluent liquids, safeguarding the health of the human beings and the receiving environment (Zindoga 2016). Therefore, this paper suggests an approach of *in situ* sanitization of fecal sludge to improve upon the most popular on-site sanitation system – the pit latrine – in order to mitigate groundwater contamination and promote a safe fecal sludge management strategy.

Based on an intensive literature search, the authors have found no review papers that focus on simultaneous collection and sanitization of fecal sludge in pit latrines. There are, however, reviews of low-cost groundwater treatment technologies for the

Table 1 | Estimated DSTN deaths by age among WHO member states, in 2016 (summarized from WHO (2018b))

	Population (thousands)		DSTN deaths (thousands)	
Country	**All ages**	**Age 0–4 years**	**All ages**	**Age 0–4 years**
World	7,429,868	673,876	1,420	482
India	1,324,171	119,998	410	103
Nigeria	185,990	31,802	186	76
Pakistan	193,203	24,963	64	37
Democratic Republic of Congo	78,736	14,494	63	33
Ethiopia	102,403	15,177	61	15

Table 2 | Estimates on the use of water and sanitation by the country (2000–2017) (summarized from WHO & UNICEF (2019b))

	Sanitation use per thousand households[a] (Percentage households, %)				Drinking water source per thousand households[a] (Percentage households, %)		
Country	**Pit latrine**	**Septic tank**	**Sewer connection**	**Open defecation**	**Piped water**	**Groundwater[b]**	**Total number of households (thousands)**
India	65,650 (28)	7,6089 (33)	24,349 (11)	59,318 (26)	100,840 (44)	112,261 (49)	230,530
Nigeria	6,951 (31)	4,180 (19)	2,245 (10)	4,439 (20)	2,505 (11)	13,295 (59)	22,415
Pakistan	3,356 (12)	9,447 (33)	7,208 (25)	2,979 (10)	8,105 (28)	17,600 (62)	28,565
Democratic Republic of Congo	4,913 (35)	759 (5)	139 (<1)	1,680 (12)	4,491 (32)	1,921 (14)	13,943
Ethiopia	1,542 (11)	310 (2)	156 (1)	3,056 (22)	4,927 (36)	3,318 (24)	13,674

[a]Number of households estimated using the average number of people per household as reported by Pew Research Center, 12 December 2019, '*Religion and Living Arrangements Around the World*'.

[b]Use of groundwater as a drinking water source is calculated as the proportion of people using non-piped − proportion of people using surface water.

removal of toxic compounds and microbial contaminants (Da'ana *et al.* 2021). Additionally, a myriad of technologies ranging from small-scale to field-scale have been tested to improve the sanitization and stabilization of fecal sludge in pit latrines, as well as other stand-alone, on-site sanitation systems. Therefore, this paper reviews these cost-efficient treatment techniques for the removal or capture of fecal pathogens in pit latrines and discusses their challenges for adoption in a pit latrine system.

APPROACH TO THE REVIEW

The relevant technologies selected for this review were derived from the Web of Science™ and the Google Scholar database using the following keywords: 'pit latrines' AND 'in-situ treatment'; 'fecal sludge' AND 'treatment'; 'fecal sludge management'; 'on-site sanitation' AND 'treatment'. Additional keywords included the major classification of pathogens' treatment and control mechanisms adopted from WHO (2018a) including 'anaerobic digestion', 'solar radiation', 'thermal treatment', 'filtration', 'chemical disinfection' and 'attenuation in the subsurface'. To provide a critical review of the literature, studies that directly assessed the fate and transport of microbes or contaminants and applied statistical methods to estimate pathogen reduction efficiency due to their intervention were characterized.

For evaluation of the sanitation technologies, the following four primary indicators were selected based on Qi-yu *et al.*'s (2021) evaluation index system: (1) economic costs (U1), (2) environmental impact (U2), (3) technical performance (U3) and (4) scope of application (U4). Each sanitation technology reviewed in this study was then ranked as 'high', 'medium' and 'low' on the basis of their overall cost of adoption (U1), ease of adoption as a stand-alone system (U2), pathogen removal/capture effectiveness (U3), treatment time (U3) and technology readiness (U4). Each indicator is given equal weightage and an overall score is determined by setting a score of 3, 2 or 1, corresponding to high, medium and low. Quantitative index parameters can be divided into either cost type (U1) or benefit type (U2, U3 and U4): the lower the cost, the better or the higher the benefit the better the index (Qi-yu *et al.* 2021). An overall rank is calculated by adding the benefit-type indicators and subtracting the cost-type indicator in the selection criterion of each technology.

PIT LATRINE TYPES AND CONSTRUCTION GUIDELINES

Pit latrines consist of a hole in the ground to collect and store human waste, a user-interface pan and a superstructure for privacy. Pit latrines, when constructed properly, can hygienically separate human excreta from human contact and reduce the transmission of fecal–oral-transmitted diseases (Hussain *et al.* 2017). This is why pit latrines were considered as improved sanitation facilities under the MDGs.

The simplest form of an improved on-site sanitation system is the single-pit, 'simple' pit latrine. A pit latrine consists of a slab over a pit that collects and stores excreta, urine and anal-cleansing material (Franceys *et al.* 1992). The aqueous phase of the collected sludge leaches into the surrounding soil, while the solid phase decomposes. The pit is dug 2 m or more in depth depending on the soil's absorptive capacity and the level of groundwater table. A minimum lateral distance of 15 m from the closest groundwater abstraction point and at least a 2 m vertical section of unsaturated soil is required between the bottom of the pit and the water table to prevent any groundwater contamination (Obeng *et al.* 2016). In areas where appropriate distances between a pit latrine and a drinking water well cannot be maintained, groundwater contamination often results in public health issues. However, this appropriate, 'safe' distance is variable for each pit latrine location as it depends on different subsurface soil types, soil hydraulic conductivity (i.e. the volume of water that moves in a unit time under a unit hydraulic gradient through a unit area), water table level, the presence of a heavy monsoon season and also with the effects of climate change in the area. Islam *et al.* (2016) conducted an in-depth field investigation in Bangladesh to determine the spread of bacteria in the subsurface from pit latrines considering different hydrogeological conditions. In this study, a clay aquitard of 18–23 m thickness reported groundwater contamination in monitoring wells located at lateral and vertical distances of 2 and 31 m, respectively. The study also showed that a thinner 9 m clay aquitard layer resulted in fecal coliform (FC) and fecal streptococci contamination of up to 4.5 m lateral and 40.5 m vertical distances.

Usually, a slab is placed firmly, raised from the surrounding ground to prevent any surface water from entering the pit (Franceys *et al.* 1992). To support the weight of the user and the slab, the top 0.5–1 m of the pit should be lined (Reed *et al.* 2016). The pits can be lined with honeycombing bricks, concrete rings, timber, stones, sandbags and even used drums to prevent the pit from collapsing in poor soil conditions (Reed 2014).

A squat-hole in the slab or any other user-friendly toilet seat is provided to hygienically collect the human wastes into the pit. Though there is no need to use water for operation of this toilet, the sludge can be a breeding ground for flies and other pests. Hence, a considerable fly nuisance is associated with this setup. In addition to the fly nuisance, there is a considerable odor emanating from the collected fecal wastes. If the superstructure around the toilet is closed without any windows, the odor can become overwhelming and difficult to use as the pit starts to fill up. To overcome the odor and flies issue, the pit can be ventilated by a pipe extending over the roof of the latrine containing a fly-proof netting (Tilley *et al.* 2014). This is now called a ventilated improved pit (VIP) latrine. In principle, the wind blowing across the top of the vent pipe effectively sucks the odorous air out of the pit and provides a circulation of fresh air into the pit through the superstructure and squat-hole (Mara 1984). A recommended ventilation rate of 20 m^3/h can be achieved by ensuring a ventilation pipe with an internal diameter of at least 110 mm and a reach of >300 mm above the highest point of the toilet superstructure (Tilley *et al.* 2014). Obeng *et al.* (2019) showed that a 0.2 m×0.7 m window only on the windward side of a VIP latrine cubicle, with a 150 mm diameter ventilation pipe consisting of an insect screen and placed 500 mm above the highest point of the roof standard, provides more than the recommended ventilation rate for a 1.2 m (L)×2.5 m (B)×3.0 m (H) pit. The vent pipe controls flies in VIP latrines in the following two ways: (1) the fly-proof netting at the top of the vent pipe prevents any flies attracted to the odors from entering the pit and (2) any adult flies bred in the pit will fly up the vent toward the brightest light, provided that the superstructure is reasonably well-shaded and get trapped by the fly-netting (Mara 1984). WHO (2002) recommends to have a tight-fitting cover for the squat-hole that is closed after each use to prevent any disease-carrying pests from escaping the pit. Obeng *et al.* (2016) provides a review of such technical design guidelines and decisions such as pit siting, ventilation, fly-control measures and pit lining for unstable soil condition for pit latrines.

On average, solids will accumulate in a pit latrine at the rate of 40–90 L/person/year varying with the use of anal-cleansing material (Gensch *et al.* 2018). Once the pit is full, it is either de-sludged and emptied for reuse or covered with soil and replaced with a new pit. In areas with ample space to build a pit latrine, a two-pit (or twin-pit) system is adopted. A two-pit system is sustainable for a longer time since it allows for continued usage once the first pit is full.

The double VIP latrine, also known as the alternating VIP latrine, contains two pits where one is used and the second idles, drains, reduces in volume and degrades (Mara 1984; Tilley *et al.* 2014). In a waterless twin-pit latrine, excreta can be covered with biodegradable organic matter and ash after each use and then left to degrade when full for a minimum of 1 year (Gensch *et al.* 2018). After a year of degradation, the pit can be dug up for using the nutrient-rich earthy-material as a soil conditioner. These pits are usually shallower (1–1.5 m deep) than other VIP toilets and can be used by a family of six for 1 year (Tilley *et al.* 2014). Such a toilet is known as the Fossa Alterna.

In a water-based toilet system, the double VIP latrine containing two alternating pits is connected to a pour-flush toilet (Tilley *et al.* 2014). These pits need to be lined to the full depth of the pit. Minimum water requirement for flushing can range from 3–6 L/person/day (directly on pit) to 6–10 L/person/day (offset) depending on the location of the pit from the user interface (Obeng *et al.* 2016). Owing to a water seal, there is reduced odor and fly nuisance in these toilets. This is the most adopted pit latrine design for households that use water for anal cleansing.

In rocky areas where digging is hard, flood-affected areas or in areas with shallow wells for drinking water, the pit needs to be partially elevated above the ground to prevent groundwater contamination. Such pit latrines are then referred to as raised latrines. These pits have a high sludge accumulation rate due to saturated or impervious soil boundaries and hence require frequent emptying and disposal strategy (Gensch *et al.* 2018).

SANITIZATION OF FECAL SLUDGE IN PIT LATRINES

Pit latrines are also responsible for unsafe return of excreta to the environment during the entire sanitation service chain (Kolsky *et al.* 2019). Some possible sources of contamination include leakage of excreta stored underground into the groundwater, spillage from emptying and transportation, inadequate treatment and illegal disposal of untreated sludge. Therefore, *in situ* sanitization of fecal sludge in a pit latrine is essential to prevent the contamination of the surrounding environment post collection of fecal matter. The following section focuses on the inactivation and capture of any fecal pathogens leaving the pit, with key information summarized in supplementary Table S1. The presented technologies are available at lab-scale, or at field-scale as a stand-alone technology, or are commercially available for local use in sludge management operations.

Technologies that disinfect/inactivate fecal pathogen

Pathogen inactivation naturally occurs inside a pit latrine due to die-off, microbial competition and predation (Orner *et al.* 2018). However, further sanitization mechanisms used commonly in wastewater treatment as well as sludge treatment can be used to inactivate pathogens in a pit. These supplementary mechanisms include microbial digestion, chemical disinfection, solar radiation, thermal treatment, sedimentation and partitioning to solids, filtration and attenuation in the subsurface (WHO 2018a).

Anaerobic digestion

Pathogens' growth and die-off occurs naturally inside a pit latrine. Human gut bacteria consume and grow on the fecal sludge in the pit latrine, converting the organic matter into CO_2 and CH_4 gases and inert residues through anaerobic digestion (AD; Foxon *et al.* 2016). Theoretically, a rate of microbial degradation higher than the rate of filling can be achieved, given the right microbes and environmental conditions (Torondel *et al.* 2016). Inside a pit latrine, the collected fecal sludge can be divided into the following four layers (Figure 1) depending on storage time, the presence of oxygen and microbial activity (Nwaneri *et al.* 2008): (1) the topmost layer contains fresh feces where biodegradation has not yet started; (2) the second layer, though quite shallow, is where aerobic hydrolysis of the stored organic material occurs; (3) the third layer is where feces undergoes anaerobic hydrolysis as a result of the elimination of oxygen by the first and second layers and finally (4) the bottom layer of the pit is where no further sludge stabilization takes place as biodegradable matter is not readily available. Nwaneri *et al.* (2008) reported a reduction in fecal pathogen as well as chemical oxygen demand (COD) content, moisture content and organic solid fraction with an increase in depth of pit contents.

Rao *et al.* (2018) modified and field-tested a twin-pit toilet in India. The first pit served as an anaerobic chamber and the second pit facilitated aerobic reactions in the upper half, with a bio-barrier in its lower half. In this twin-pit system, the anaerobic reactions reduced COD by 72%, while aerobic reactions reduced thermotolerant coliform counts by 2.5 log cycles. Denitrification reactions in the bio-barrier reduced ammonium and nitrite present in the raw sewage entering the pit to nitrogen and water. This reaction was limited by the COD/N ratio favorable for ammonium oxidation in the aerobic chamber. Another study from sub-Saharan Africa reports that small-scale ambient temperature AD systems can result in 2–3 log reductions of indicator coliform bacteria from human and animal wastes (Avery *et al.* 2014).

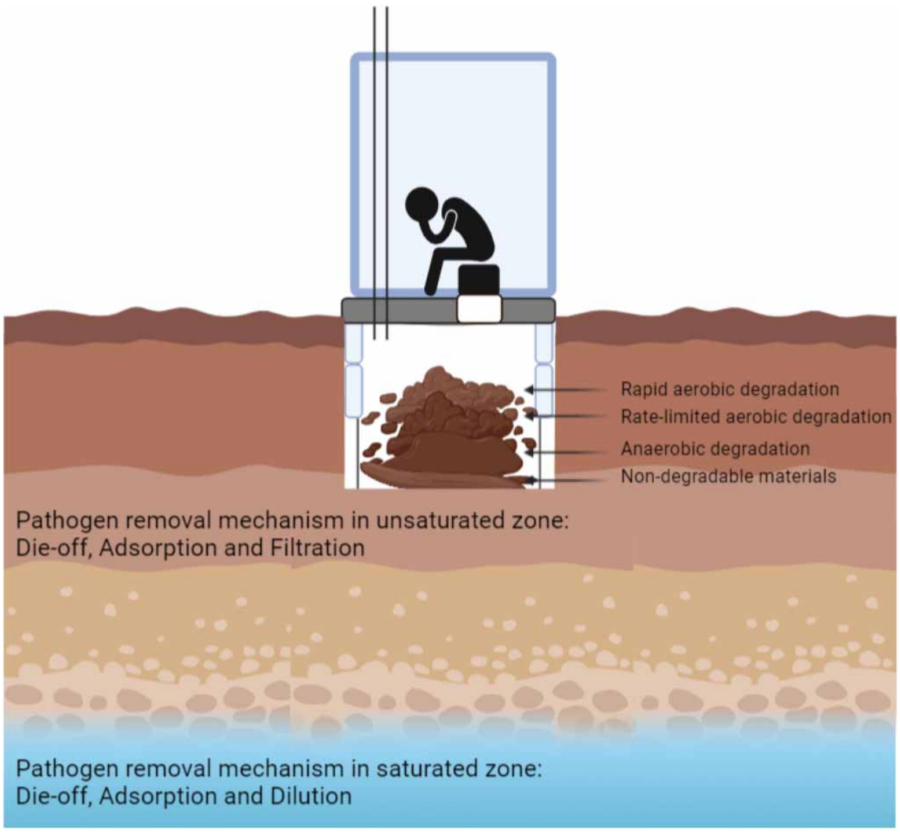

Figure 1 | Pathogen removal process in the saturated and unsaturated zones surrounding the toilet pit (adapted from Orner *et al.* (2018)).

Chemical and biological disinfection

During disaster events or humanitarian emergencies where important losses and damage are inflicted upon communities and individuals, immediate assistance is essential to stabilize the situation and enhance recovery (Reed *et al.* 2016; Gensch *et al.* 2018). In such emergency situations, pit latrines and container-based toilet systems (CBSs) are most commonly used sanitation technologies for decentralized fecal sludge management (Zindoga 2016). Chemical disinfection using chlorine solutions and hydrated lime (HL) treatment are hence an effective strategy for pathogen reduction, which are used mainly in emergency settings due to their short treatment times. Hypochlorite or bleach solutions are added to holding tanks filled with sludge collected from pit latrines or CBS to oxidize the microorganisms and organic matter (Tilley *et al.* 2014; Silva *et al.* 2018). Contrarily, HL suspensions are added to leak-proof tanks containing fecal sludge to create an alkali environment causing pathogen deactivation (Gensch *et al.* 2018). Additionally, when mixed with fecal sludge, the lime may also act as a coagulating agent. The coagulation–flocculation process results in pathogens and organic material to adhere to solid flocs that can be removed by a subsequent sedimentation process (Silva *et al.* 2018). It is important to note that subsequent treatment processes may still be needed to ensure there is no pathogen regrowth and proliferation in the sludge for maintaining WHO-recommended limits of disinfection using chemical additives (Kumwenda 2019; Zhao & Liu 2019).

Chemical disinfection is more effective at higher dosages that can be achieved by increasing concentration and treatment time (i.e. CT values). A HL 30% suspension results in a greater log reduction (FC = 4.75; intestinal enterococci (IE) = 4.16; somatic coliphages (SOMPH) = 2.85; F^+-specific bacteriophages (F+PH) = 5.13 and bacteriophages infecting *Bacteroides fragilis* (GB124PH) = 5.4) than a HL 10% suspension (FC = 1.69, IE = 1.09, SOMPH = −1.31, F+PH = 2.77 and GB124PH = 4.66) and the best performing 0.5% NADCC (sodium dichloroisocyanurate or SIDC 65%; Minstral®) suspension (FC = 2.90, IE = 2.36, SOMPH = 3.01, F+PH = 2.36 and GB124PH = 0.74) (Silva *et al.* 2018). Zindoga (2016) batch-tested a 7% (w/w) dose for Ikati (naturally mined carbonate) and Soda (sodium carbonate) on a freshly collected fecal sludge from a container-based urine-diverted dry toilet and achieved a 4-log reduction in *Escherichia coli* concentration after 24 h and a concentration below the detection limit (1,000 cfu/100 mL) after 48 h. A study of commercially available chemical additives for household toilets, using calcium carbide and Lambda Super 2.5 EC™ (an agrochemical containing the active compound lambda-cyhalothrin) to treat fecal sludge, resulted in a moisture content reduction between 39 and 74%, 5-day biochemical oxygen demand (BOD_5) by 30–47%, total coliform by 79–98.5% and helminth eggs by 82–99.6% (Appiah-Effah *et al.* 2020).

There are commercially available chemical additives and bio-additives that claim to reduce the sludge accumulation rate in a pit latrine by enhancing biological activity. Kemboi *et al.* (2018) demonstrated the efficacy of 11 additives on the stabilization and sanitization of pit latrine fecal sludge including chemical additives such as Ikati, Soda and Safety Gel™, and biological additives such as Biomax™, EM (effective microorganisms), Aquaclean™, Saniloo™, Rid X™, Terraktiv™, Men xu ly be phot™ and Magic Pit™. The biological additives showed no or little evidence of increased anaerobic activity and of reduced volatile solids and *E. coli* concentrations when compared to the addition of water or inert additives, as was found by studies using similar additives (Foxon *et al.* 2009; Bakare *et al.* 2010; Kemboi *et al.* 2018). However, some biological additives did show limited success in laboratory tests. The manufacturer's recommended dosage for two commercial bio-additives: Ecotreat™ (4% w/w) and Sannitree™ (3.3% w/w) achieved a 2-log reduction in *E. coli* concentration after 48 h (Zindoga 2016). On the contrary, the chemical additives, such as Ikati and Soda, used by Kemboi *et al.* (2018), resulted in a significant reduction in *E. coli* concentrations due to an increase in pH caused by the presence of carbonate and hydroxide ions.

A promising application of biological disinfection is lactic acid fermentation of fecal sludge with fermented food wastes. Odey *et al.* (2018) reported an effective inactivation of FC and *E. coli* using fermented rice flour and fermented milk, respectively. A laboratory-scale experiment demonstrated a Log 4, Log 5.5 and Log 7.5 reduction in total coliform concentration in fecal sludge after 21 days using a non-specified microbial culture (EM4) as the inoculum and 0, 5 and 10% (w/w) glucose as the substrate (Soewondo *et al.* 2014). Similarly, Anderson *et al.* (2015) compared lactic acid fermentation of fecal sludge (10% wet weight molasses and 10% wet weight pre-culture) with chemical disinfection (7–17% (w/w) HL suspension and 2.5% (w/w) urea treatment). This study demonstrated a >2.5, >3.7 and >2.2 log removal of *E. coli* using lactic acid fermentation within 168 h, urea treatment within 96 h and HL suspension within 1 h, respectively.

Solar pasteurization

Solar energy has been applied for fecal sludge drying in greenhouses and in open fields, though its use is minimal in the sanitation sector. Solar drying of fecal sludge from pit latrines in bench-scale tests resulted in an average drying rate between 0.5 and 0.8 kg/h/m^2 (Septien *et al.* 2018). Ward *et al.* (2014) investigated a solar-powered pyrolysis reactor known as the Sol-char toilet to convert fecal sludge from pit latrines into pathogen-free biochar. Another solar thermal water heater system was tested at laboratory scale to dry and disinfect fecal sludge (Sweya & Mgana 2020). This system showed a 100% reduction in total coliform and FC in 13 and 42 days for dry and wet seasons, respectively, while the sludge water content decreased from 99.32 to 5.3% and 81.57 to 5.5% in 40 and 54 days of dry and wet seasons, respectively. Redlinger *et al.* (2001) presented a stand-alone, single-vaulted, solar-composting, dry sanitation system called Sistema Integral de Reciclamiento de Desechos Orgánicos (SIDRO). Within 6 months of operation, the system was capable of producing U.S. Environmental Protection Agency standard Class A (<1,000 most probable number (MPN) FCs per gram) and Class B ($<2\times10^6$ MPN FCs per gram) compost with safe and acceptable levels of pathogens.

Vermicomposting

Pathogen removal from pit latrines using detritivorous worms such as black soldier fly (*Hermetia illucens*) and tiger worms (*Eisenia fetida*) to process human excreta has been tested in low- and middle-income countries (Banks 2014; Furlong *et al.* 2016; Hylton *et al.* 2020). Furlong *et al.* (2016) trialed the use of 'Tiger toilets', a pour-flush toilet linked to a vermifilter (a filter containing tiger worms) in 10 rural households in India for a period of 12 months. The effluent collected had a reduction of 57 and 99% in COD and FC, respectively, with accumulation of little fecal solids, generation of low odors and an overall safer emptying (Furlong *et al.* 2016; Hylton *et al.* 2020). Previous studies for biosolid treatment using tiger worms have resulted in 98.65% reduction in FCs over a 24-h period (Eastman *et al.* 2001). Banks (2014) suggests using black soldier fly larvae (BSFL) for vermicomposting in pit latrines due to their (1) suitability for artificial rearing, (2) ability to develop on and efficiently reduce a variety of organic materials, yielding a valuable prepupae high in protein and fat which can be used as a protein source for animals or have fats transformed to biodiesel and finally (3) their ability to reduce pathogens in chicken, dairy manure and human feces. In a laboratory study, Lalander *et al.* (2013) showed that BSFL accelerated the reduction of *Salmonella* spp. in human feces; however, there was no significant impact on the concentrations of *Enterococcus* spp., bacteriophage ΦX174 or *Ascaris suum* ova.

Technologies that capture fecal pathogens

Fecal pollution of groundwater from pit latrines is severe and spatially or temporally continuous in the near-field that is restricted for a few meters in alluvial-deltaic terrains (Ravenscroft *et al.* 2017). However, when the fecal pathogen leaches out into the soil saturated with water, it can travel great distances (>20 m from pit), at faster rates, than in unsaturated soils and persist longer (up to 42 days) (Banerjee 2011; Graham & Polizzotto 2013; Islam *et al.* 2016). Hence, it is also important to capture the pathogens in the pit, slow their transport out of the pit or treat the percolating liquid before it reaches the groundwater.

The soil surrounding a pit latrine acts as a natural physical barrier to the pathogens in fecal sludge. In addition to physical filtration, soil adsorption can also retard the movement of bacteria and other microorganisms. Depending on the pore size of the soil, the percolating liquid is filtered and pathogens are adsorbed on the soil particles (Islam *et al.* 2016). Nichols *et al.* (1983) stipulated that factors which reduce the repulsive forces between bacteria and soil surfaces would enhance the adsorption. For example, the coliform filtration efficiency of sand increases with a decrease in pH, while the presence of clay enhances the bacterial adsorption. The introduction of adsorbents to the pit surface has been tested in the form of liners.

In addition to adsorption, large microorganisms such as protozoans and helminths often cannot escape out of the pit due to their size. The soil–sludge boundary acts as a biofilm where pathogen die-off occurs due to microbial competition and changing redox environments (Orner *et al.* 2018). The indigenous soil microbial population has even shown to compete with fecal bacteria for the same organic content present in the sludge causing pathogen die-off, sometimes even predation (Orner *et al.* 2018). Hence, permeable reactive barriers (PRBs) can potentially react and sanitize the outgoing leachate. This section focuses on a number of potential interventions that have been tested in the laboratory or in the field.

Pit latrine liners

To capture pathogens inside a pit latrine while promoting *in situ* fecal sludge drying and stabilization, commercial hydrophobic laminate liners such as Gore-Tex™ and eVent™ fabrics were proposed by Marzooghi & Dentel (2014). Preliminary small-scale laboratory experiments showed municipal wastewater biosolids drying from a moisture content of about 97% to 12–30%, and permeate is observed to be free of FC (Marzooghi *et al.* 2017). Field testing of a hydrophobic laminate-lined 208-L and 40-L CBS referred to as eco-vapor toilets was conducted in Kanpur, India. Saxena *et al.* (2021) increased the time taken to fill a conventional CBS by at least 19% due to the enhanced *in situ* drying of fecal sludge. However, the study did not check for pathogen retention or die-off inside the laminate-lined container. Since most pathogenic bacteria are inactivated by moisture reduction to a threshold water activity (Remington *et al.* 2020), pit latrines with commercial hydrophobic laminate liners have been proposed in order to mitigate fecal contamination of groundwater (Figure 2).

To reduce the hydraulic conductivity of the soil surrounding the pit, sandbag lined pit latrines or '*birkaroons*' were first installed in Dadaab refugee camps in north eastern Kenya (Barasa 2000). This is an eco-friendly and cost-effective way to line toilets in emergency situations. Naser *et al.* (2019) reported a reduction of 27% *E. coli* and 24% thermotolerant coliform mean counts in pit latrines using a 50-cm thick sand barrier in coastal Bangladesh. Similarly, Banerjee (2011) demonstrated that clay enveloped around a leach pit toilet arrests the movement of chemical and bacteriological pollutants to a considerable extent. In another study, the movement of FC was completely arrested in pit latrines using a peat liner containing a mixture of sphagnum and reed-sedge peat (Nichols *et al.* 1983). However, nitrates were able to move readily from the pit latrines regardless of the soil type or the presence of a peat liner. In emergency situations, Reed *et al.* (2016) highlights the use of other types of liners including bore piles, concrete rings, corrugated steel roofing sheets, timber, bamboo, plastics, geotextiles and gabions that may have helped capture fecal bacteria and other chemical constituents. However, impermeable or improper linings led to flotation of sealed pits, or worse, an eventual collapse of the pit.

Permeable reactive barriers

A possible solution to mitigating groundwater contamination is to augment pit latrines with a PRB that can selectively adsorb and remediate the leachate. PRBs are widely used where contaminated groundwater flow passes over a reactive material such as zero-valent iron, limestone, microorganisms, straw, peat and others, for immobilization or passive contaminant degradation (Da'ana *et al.* 2021). Suhogusoff *et al.* (2019) field-tested a pit latrine improved with a PRB composed of locally available materials: basic oxygen furnace slag and sawdust. The effluent had completely attenuated microorganisms and phosphate, while nitrate removal average efficiency was 42%. Similarly, Rao & Malini (2015) demonstrated heterotrophic denitrification capability of bentonite-enhanced sand PRB by reducing nitrate concentration by 85–90% in batch and column tests. Rao *et al.* (2018) also successfully field-tested a modified twin-pit toilet that used a bio-barrier constructed using sand, gravel and cattle manure mixers to facilitate denitrification reactions (see supplementary Table S1).

DISCUSSION

WHO (2018b) provides general safety guidelines for pit latrine construction, while Tilley *et al.* (2014) and Gensch *et al.* (2018) present a comprehensive list of sanitation systems and technologies including their appropriateness, design considerations, advantages and disadvantages in rural, peri-urban and high-density urban areas as well as in emergency situations. However,

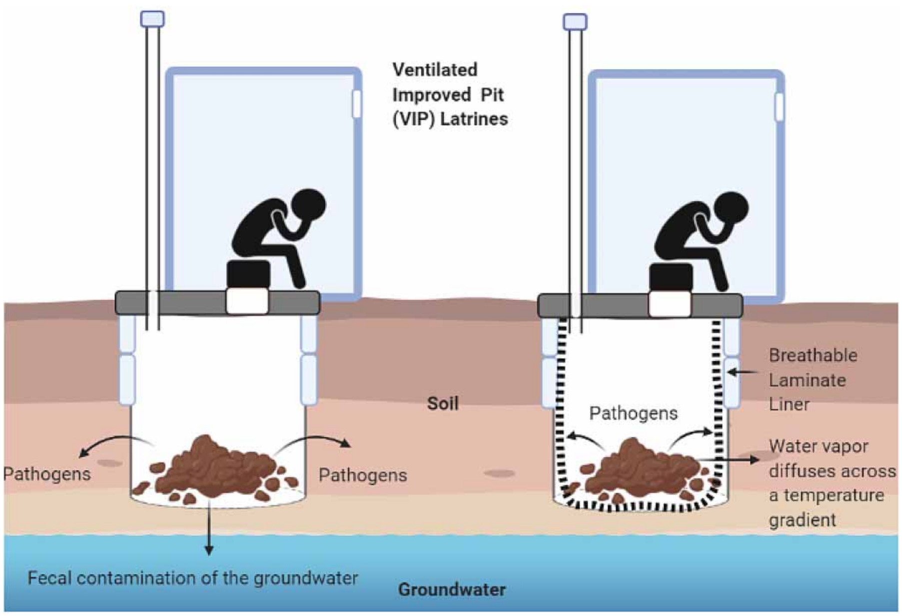

Figure 2 | Transport of fecal pathogens in a VIP latrine. The breathable laminate liner inside a pit latrine captures pathogens while allowing drying of fecal sludge.

a big challenge is to disseminate this information to the local masons and sanitation workers who are responsible for toilet construction and maintenance. These masons often lack formal training or the ability to disseminate the correct technology options to the user (Roberts *et al.* 2007). This results in poor toilet design, construction and maintenance, thereby causing non-adoption of safe-sanitation practices and eventually reverting people back to unsafe sanitation practices including OD (Busienei 2019). The following section looks at some challenges in adopting the above-mentioned technologies for modifying on-site sanitation systems to safe-sanitation systems.

Practical implications and challenges of *in situ* sanitization in pit latrines

For years, AD has been used for the treatment of municipal wastewater and is considered highly efficient for inactivating pathogens. Physiochemical factors such as high temperature, high uncharged aqueous ammonia concentration at high pH and high volatile fatty acids at low pH have shown to increase the rate of deactivation of FC, polio virus, ascaris egg and other pathogens during AD of biosludge (Orner *et al.* 2018; Zhao & Liu 2019). However, AD is slow in nature and requires very long storage times (recommended 1–2 years depending on the pit volume) to eradicate the pathogen completely (WHO 2018a). Avery *et al.* (2014) documented that the efficiency of AD is dependent on the operating temperature, hydraulic retention time, solids retention time and composition of sludge.

Chemical disinfection, though simple, has an associated health risk from storage and handling of the corrosive chemicals. Usually, chemicals need to be mixed with the sludge to be effective. Chlorine-based disinfectants are known to form toxic disinfection by-products with the organic matter in fecal sludge, while HL treatment has a highly alkaline effluent that can leach into the groundwater if used *in situ* to treat pit latrine wastes (Anderson *et al.* 2015; Gensch *et al.* 2018). On the contrary, there are inconclusive results from commercially available chemical and biological additives for pit latrines. Foxon *et al.* (2016) note that there is a potential significant enhancement in the rate of AD inside a pit latrine. However, the variability in pit latrine design, fecal sludge contents, local conditions and cost-effectiveness makes additives an unreliable technology. Furthermore, the fermentation process promoted by biological additives itself is highly susceptible to environmental conditions, culture used for fermentation and its mixing conditions. The treated sludge may require additional processing for sludge stabilization (Gensch *et al.* 2018). Furthermore, the chemical and bio-additives are costly compared to the use of proven chemical disinfection using HL and even other chlorine-based interventions. Anderson *et al.* (2015) report that the cost of sanitizing 1 m^3 of fecal sludge was estimated to be €32, €20 and €12 for lactic acid fermentation, urea treatment and HL suspension, respectively, based on Malawian prices in 2015.

Decentralized sanitation technologies using solar pasteurization and vermicomposting are still under-developed and evolving. Solar-based technologies are limited to the exposure to sunlight reaching the fecal sludge, and its use for sanitization in pit latrines will be dependent on the water/sludge depth, clarity of sludge and exposure time (WHO 2018a). Currently, there is no evidence of technologies using the germicidal effects of sunlight inside pit latrines. On the contrary, vermicomposting- and vermifiltration-based sanitation systems have demonstrated effective reduction of *E. coli* and other indicator organisms in lab- and field-scale studies (Lalander *et al.* 2013; Hylton *et al.* 2020). However, there is still a knowledge gap with regard to effects on other pathogens found commonly in fecal sludge, and vermicomposting and vermifiltration efficiency with parameters such as temperature, rainfall intensity, sludge content and worm species.

To capture pathogens, pit latrine liners such as sandbags, peat liners, clay envelopes and PRBs have been successfully applied in rural, urban and even in emergency situations. Yet, the reduction of pathogens inside a pit and their transmission of contaminants to the groundwater remain highly dependent on the level of water table, rainfall, hydraulic conductivity of the soil and its relative location to the nearest water-pump (Ravenscroft *et al.* 2017). Hence, to capture contaminants and to provide a safe end-to-end sanitation chain, Russel *et al.* (2019) argue that CBS is a good alternative to pit latrines. In a CBS, fecal matter is collected and stored in sealable containers which are transported to a treatment site when the container is full. CBSs have recently gained popularity in high-density, informal, urban and peri-urban settlements of developing countries such as Madagascar (Loowatt), Kenya (Sanergy, Sanivation), Haiti (SOIL) and Peru (X-runner) (Dewhurst *et al.* 2019). However, the success of a CBS needs the support of an auxiliary sanitation service chain for proper collection, transportation, disposal and treatment of fecal sludge containers. Though still a nascent technology, a field-scale hydrophobic laminate-lined CBS demonstrated the ability to capture and dry fecal sludge when applied in urban-slum households (Saxena *et al.* 2021). Consequently, hydrophobic laminate liners might be touted as a potential technology capable of capturing pathogens and contaminants safely inside a CBS or a pit latrine with the possibility of *in situ* sanitization and stabilization of fecal sludge (Marzooghi & Dentel 2014).

Table 3 | Comparison of pathogenic contamination containment methods for pit latrines

	Cost-type indicator	Benefit-type indicator				
	Economic cost (U1)	Environmental impact (U2)	Technical performance[a] (U3)		Scope of application (U4)	
	Overall cost of adoption[b]	Ease of adoption[b]	Pathogen removal effectiveness	Treatment time	Technology readiness[c]	Overall score[d]
AD (Rao *et al.* 2018)	Low	Low	Medium	Low	Low	2.5
Chemical disinfection (chlorine/lime treatment) (Trajano *et al.* 2019)	Low	High	High	High	High	8
Solar pasteurization (Redlinger *et al.* 2001)	High	Medium	Medium	Low	Medium	2.5
Thermal treatment (Naidoo *et al.* 2020)	High	Medium	High	High	Low	3
Pit latrine additives (Ikati/Soda) (Zindoga 2016)	Low	High	Medium	High	High	7.5
Biological disinfection (lactic acid fermentation) (Odey *et al.* 2018)	Medium	Medium	Low	Medium	Low	2.5
Vermicomposting ('Tiger' toilets) (Furlong *et al.* 2016)	Medium	Medium	High	Medium	Medium	4.5
	Cost-type indicator	Benefit-type indicator				
	Economic cost (U1)	Environmental impact (U2)	Technical performance[a] (U3)		Scope of application (U4)	
	Overall cost of adoption[b]	Ease of adoption[b]	Pathogen removal effectiveness	Potential for contaminant removal	Technology readiness[c]	Overall score[d]
Pit liner (sandbags) (Naser *et al.* 2019)	Low	High	Low	Low	High	6.0
Pit liner (clay envelope) (Banerjee 2011)	Low	Medium	High	Low	High	6.0
Pit liner (peat) (Nichols *et al.* 1983)	Low	High	High	High	Medium	7.0
Pit liner (hydrophobic membranes) (Marzooghi *et al.* 2017)	High	Medium	High	Low	Low	2.0
Permeable reactive barriers (Suhogusoff *et al.* 2019)	Medium	Low	High	High	Low	3.0
Container-based toilet (Russel *et al.* 2019)	Medium	Medium	High	Low	High	5.0

[a]The treatment performance for each technology is summarized in Supplementary material, Table S1.
[b]Ease and overall cost of adoption rank technologies based on the additional requirements for infrastructure and maintenance when compared to a standard ventilated pit latrine system. This also includes the ease and cost of acquisition of materials and services. For example, hydrophobic membranes will be more difficult and costlier to procure than sandbags, clay and peat, while hydrophobic membrane and clay envelope toilets will require more frequent pit emptying than a standard pit latrine.
[c]Technology readiness compares the robustness of each technology; 'High' for conventional, frequent use, 'Medium' for field implementation with 100 s of units, 'Low' for laboratory studies or field studies with 10 s of units in operation.
[d]Overall score adds the benefit-type and subtracts the cost-type quantitative indicators for each technology. 'High', 'Medium' and 'Low' are assigned a value of 3, 2 and 1, respectively. For example, overall score for container-based toilet $= -2 + 2 + (3 + 1)/(2) + 3 = 5$.

Comparison of treatment technologies

Currently, an accurate comparison for the cost of fecal sludge treatment technologies is difficult due to the following problems: (1) extrapolation of reported cost under specific conditions at one site to another site; (2) costs could be reported in various metrics that cannot be directly compared, such as the achieved reduction in contaminants and the cost per treated volume or surface area treated; (3) indirect costs, including system design, equipment mobilization, modification to site conditions and user awareness, are usually not reported and finally (4) inconsistency in the way technologies at different stages of development derives the total cost of treatment (Da'ana *et al.* 2021). Additionally, the selection of the best-available technology for the mitigation of groundwater contamination is difficult. Hence, to give a top-level, comprehensive comparison, Table 3 ranks each of the above-mentioned technologies as 'high', 'medium' and 'low' on the basis of their pathogen removal/capture effectiveness, ease of adoption as a stand-alone system, treatment time, overall cost of adoption and technology readiness. An overall score is determined by aggregating high (3), medium (2) and low (1) ranks for benefit-type and cost-type quantitative indicators in the evaluation criterion of each technology (Qi-yu *et al.* 2021). As a result, the chemical disinfection using chlorine and lime, pit latrine additives using Ikati and Soda and peat liners for pit latrines have the highest score, likely attributed to their robustness as a technology in wastewater management. On the contrary, AD adopted pit latrines by Rao *et al.* (2018), solar technology or SIDRO toilets adopted by Redlinger *et al.* (2001), lactic acid fermentation technology by Odey *et al.* (2018) and hydrophobic membrane lined toilets proposed by Marzooghi *et al.* (2017) had the lowest scores. Although the scoring method inevitably works in favor of robust technologies versus developing, field-scale technologies, it serves to highlight the areas of a technology still facing challenges to gain market acceptability and user adoption as a stand-alone *in situ* treatment system.

CONCLUSIONS

In conclusion, safe water, sanitation and hygiene (WASH) practices are still the best barriers to human exposure to fecal pathogens. Hand washing, improved toilets, safe containment, conveyance, treatment, end use and disposal, access to clean drinking water as well as source water protection are all important in order to prevent transmission of fecal pathogens to humans and the environment. *In situ* treatment of fecal sludge in pit latrines may be a viable option to mitigate groundwater contamination and prevent contamination at various points in the sanitation chain. Though the selection of the best technique needs to be decided on a case-to-case basis due to variability in the risk of transmission of pathogens from sanitation technologies to humans and the environment. This research provides a comparative ranking to the several treatment options on the basis of sanitization or captures the efficiency of fecal pathogens, ease of adoption, cost, treatment time and potential, and technology readiness. Finally, it is recommended that future research efforts focused on developing safe fecal sludge management technologies and techniques can also be systematically ranked for pragmatic selection of technologies by WASH professionals, field practitioners and other key stakeholders.

FUNDING

This publication was funded by Grand Challenges Canada under the 'Creating Hope in Conflict – A Humanitarian Grand Challenge' (funding no. R-HGC-POC-2007-35575).

DATA AVAILABILITY STATEMENT

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

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First received 28 September 2021; accepted in revised form 18 November 2021. Available online 20 December 2021