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Application of black soldier fly larvae in decentralized treatment of faecal sludge from pit latrines in informal settlements in Kampala city

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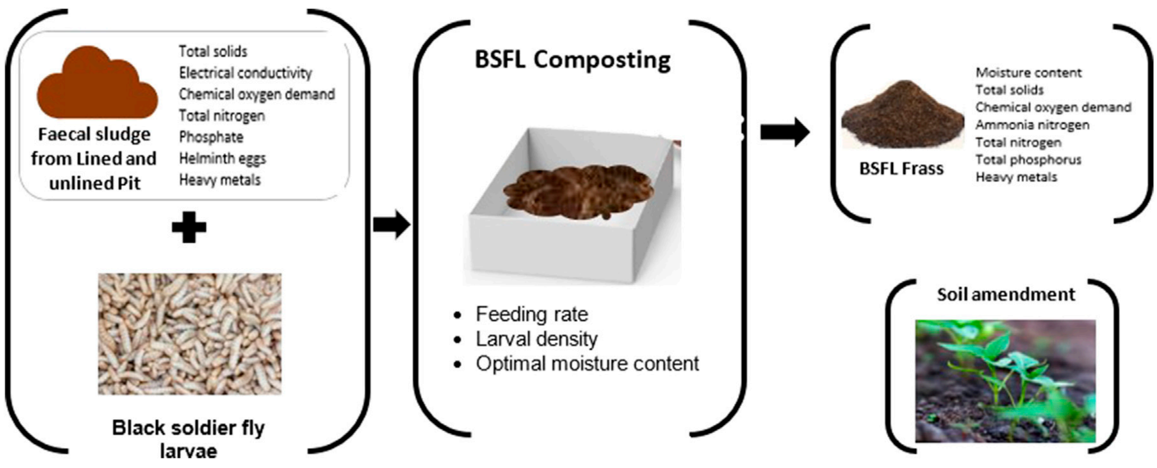
Introduction: Faecal sludge management (FSM) in urban areas of low-and middle-income countries (LMICs) is not properly implemented due to inaccessibility of sanitation facilities and high faecal sludge (FS) emptying costs, amongst others. Unlike in solid waste and fresh human excreta, use of black soldier fly larvae (BSFL) in treatment of FS from pit latrines - which are the most common sanitation facilities in urban areas of LMICs - has not yet been explored. Moreover, the optimal conditions for efficient FS degradation, such as moisture content, feeding rate and larval density are not yet well known. Against this backdrop, the overarching aim of this study was to determine the effectiveness of BSFL in treating FS under different conditions of moisture content, feeding rate and larval density. Also, the quality of residue left after treatment was assessed.

Methods: FS samples were collected from lined and unlined pit latrines in Bwaise I parish in Kampala, Uganda and experiments were set up to feed 10-day old larvae.

Results and Discussion: The optimum feeding rate, larval density and moisture content were found to be 50 mg/larvae/day, 1.33 larvae/cm^2 and 60%, respectively. The reduction efficiency at optimum conditions were 72% and 66% for FS from lined and unlined pit latrines, respectively. It was further noted that BSFL can feed on FS from pit latrines without dewatering it, hence there is no need for a dewatering unit. The properties of the residue left after treatment were within the allowable limit for use as compost except for helminth egg concentration. Thus, in informal urban settlements, BSFL can be applied for effective treatment of FS from pit latrines while generating good quality residue thereby providing an additional value chain in FSM.

KEYWORDS

black solider fly larvae, faecal sludge reduction, informal settlements, pit latrine faecal sludge, black solider fly, faecal sludge treatment, on-site sanitation system



GRAPHICAL ABSTRACT

1 Introduction

Globally, about half of the world's population make use of onsite sanitation systems for their sanitation needs (WHO/UNICEF, 2021). Majority of the urban population in Sub-Saharan Africa (SSA) use pit latrine (a form of onsite sanitation system) as their primary means of excreta disposal. In informal settlements (usually occupied by low-income earners), household pit latrines are mainly shared by a large number of people resulting in high filling rates (Nakagiri et al., 2015; Manga et al., 2022a). However, the management systems in place for the resulting accumulated faecal sludge (FS) are still challenging (Strande, 2014). FS comprises all liquid and semi-liquid contents of on-site sanitation systems, such as pit latrines, aqua privies and septic tanks. It is reported to be 10 to 100 times more concentrated in suspended and dissolved solids than wastewater (Heinss et al., 1998; Manga et al., 2016). FS can also vary in characteristics according to sources such as septic tanks, public toilets containment systems and pit latrines. In most cases, FS in pit latrines is thick and cannot be easily emptied with vacuum trucks (Semiyaga et al., 2022a). When emptied, FS from pit latrines can be treated at designated plants, where preliminary treatment involving removal of large amounts of solid wastes, silt, and the thick FS is often mixed with water (Semiyaga et al., 2022b). In addition, sedimentation in settling thickening tanks separate solid and liquid fractions; treatment of liquid fraction in waste stabilization ponds and drying of solid fractions on the sand bed are carried out (Manga et al., 2016; Manga et al., 2017). However, high emptying and transportation costs which cannot be met by the residents in informal settlements limit the effective management of FS. Consequently, these pit latrines are often opened up to discharge FS into the environment and drainage channels whenever it rains. This poses huge environmental and public health risks to the urban communities (Kulabako et al., 2010).

Application of decentralized (onsite) FS treatment facilities/systems promotes initiatives which can allow FS to be emptied, treated and used at and/or near the point of generation leading to reduced transportation costs (Semiyaga et al., 2015). Several available options for decentralized treatment of FS such as composting, vermi-composting, anaerobic digestion, rendering have been applied for the treatment of FS (Cofie et al., 2009; Manga et al., 2021; Semiyaga, et al., 2022a; Manga et al., 2022b). However, these techniques have some limitations. For instance, composting is a slow process which may take months if not operated with aeration, turning as well as right environmental conditions (Manga et al., 2019). Vermi-composting has large space requirements and earthworms are usually very sensitive to salt contents in their feedstock (Munroe, 2007). A novel solution for FSM at a decentralized-scale such as the use of black soldier fly larvae (BSFL) could be a viable option under informal settlement conditions. BSF belongs to the family of *Stratiomyidae* and order of *Diptera* and thrives in both tropical and temperate regions worldwide (Singh and Kumari, 2019). The larvae is saprophytic and has powerful digestive enzymes which helps in breaking down various organic wastes (Liu et al., 2019; Cho et al., 2020); under ideal conditions, the larvae can significantly reduce the volume of organic waste by up to 50% or more (Gold et al., 2020). They also produce large quantities of larvae and prepupae which can be used as animal feed source as it is composed of protein and fat as high as 40% and 30%, respectively (Cummins et al., 2017; Nyakeri et al., 2019, Arnone et al., 2022). Also, their excruviae and the residue left after treatment (frass) can be used in the production of organic fertilizer (Webster et al., 2016; Beesigamukama et al., 2021).

Different kinds of organic waste such as pig manure, food waste, municipal waste have been used as substrates for treatment with BSFL and the optimal conditions for their treatment have also been investigated (Diener et al., 2011; Jucker et al., 2017; Manurung et al., 2016; Supriyatna et al., 2016). A few studies have reported treating of FS with BSFL, though these are not based on FS from pit latrines which are the most common sanitation facilities in informal settlements in SSA (Lalander et al., 2013; Nyakeri et al., 2019; Peguero et al., 2021). Pit latrine FS physicochemical and microbiological characteristics differ from other sanitation systems as it contains various types of solid wastes, chemicals for reducing pit content and smell and at times take long to be emptied. Indiscriminate use of different anal cleansing materials by pit latrine users make the FS characteristics from these facilities differ from the many studies done on sludge from septic tanks and fresh faecal matter. Also, some of these studies have been carried out in rural settings (Furlong et al., 2015) and the results cannot be transferred to the urban informal settlements where performance of the sanitation systems are affected by differences in user habits and high number of users. In the study by Furlong et al. (2015) in rural India, it was observed that smaller larvae density (2 kg/m^2) was more efficient in the degradation of organic matter than larger larvae density (4 kg/m^2). In urban slums of Kampala Uganda, the most common sanitation facilities are lined and unlined pit latrines. FS from pit latrines ranges from a slurry, to semi-solid paste (lined pit latrine) and at time a solid sludge (unlined pits) (Jördening and Winter 2005; Velkushanova and Strande, 2021). The unlined pit wall of most of these latrines allow infiltration and exfiltration of moisture. Since FS characteristics are known to influence the performance of BSFL (Diener et al., 2011; Banks et al., 2014), it is imperative that use of BSFL in treatment of FS from both lined and unlined pit latrines is studied. . Also, with the limited research in the use of BSFL for the treatment of FS, optimum conditions for factors such as moisture content, feeding rate and larval density which influence the efficiency of BSFL in treating FS are not yet well known. Specifically, not much is known about the production of BSFL frass from pit latrine FS. Knowledge gaps exist in the nutrient and microbial composition of BSFL frass from FS, its usage and benefits in agriculture and other cultivation related activities. To this end, the overarching aim of this study is to investigate the capacity of BSFL in treating FS from lined and unlined pit latrines in informal settings. Specifically, the study investigated: 1) suitability of FS from lined and unlined pit latrines as feedstock for BSFL; 2) optimal feeding rate, larval density, and moisture content for the treatment of FS with BSFL; 3) quality of the resulting residue and its suitability as organic fertilizer. The results are relevant in designing and implementing scalable and sustainable decentralized systems using BSFL within informal settlements. This can create additional value chain which can generate revenue for the sustenance of faecal sludge management chain in informal settlements.

2 Methodology

2.1 Study area

This study was carried out in Bwaise I Parish located in Kawempe division, Kampala Capital City in Uganda. Bwaise I has about 7,500 households with an average size of five people. The place is characterized by informal settlement patterns with very small plots, barely enough for the construction of both the living house and individual sanitation facilities (KCCA, 2015). This results in the inability of motorized vacuum trucks to access and empty full latrines. Bwaise I was selected based on the fact that residents rely heavily on shared pit latrines as the means of excreta disposal and contains both lined and unlined pit latrines.

2.2 Faecal sludge sampling strategy and preparation

The pit selection was carried out in collaboration with *Terikigana* Sanitation Services, an organization of local pit emptiers based in Kampala. They helped in identifying pit latrines that could be used in the study area. A total of 12 lined and 12 unlined pit latrines were purposively selected. The selection criteria included willingness of the latrine owners to participate in the study; availability of more than one stance per pit latrine so that residents could still access the latrine during periods of sampling; and the latrine facility had to be nearly full to provide sufficiently large quantity of FS content and depth for sampling (minimum sludge depth of 1.5 m). Due to the variation in the construction details of pit latrines and in turn, resulting faecal sludge characteristics, a clear distinction had to be made between lined and unlined pits.

From each pit, a total of four samples were taken from depths of 0.1 m, 0.5 m, 1.0 m and 1.5 m below the sludge surface using a multi-stage sampler reported in Semiyaga et al. (2017). One litre of FS was picked from each depth and collected in a container, where it was thoroughly mixed to obtain a composite sample. The collected composite samples were kept in labelled containers to easily differentiate them during analysis. At this point, the parameters of temperature and pH of the extracted FS were taken using a portable meter (Hach HQ30d flexi model). The samples were then preserved by storing at a temperature of 4°C in a cooling box and transported to the Public Health and Environmental Engineering (PH & EE) laboratory at Makerere University, Kampala Uganda for further analysis. Prior to BSFL experiments, FS samples were screened through a 5 mm sieve to remove extraneous materials such as clothes, pads, polythene bags, condoms, and bottles to remove materials which cannot be fed on by BSFL.

2.3 Collection of black soldier fly larvae

The BSFL used in the experiments were obtained from a colony at a private breeding place in Bombo Sub-County, Luwero district in Central Uganda; this was also the site for the experimental setup. One day old BSF eggs were collected from the colony using cardboards placed inside the BSF cage. The cardboards with the eggs were removed from the BSF cage and placed in a confined area for 3 days to allow the eggs hatch into larvae. The larvae and layer mash (which served as a food source for hatched larvae) were stored for 10 days. The 10-day old larvae were then separated from the feedstocks to be used in the experiments. 10-day old larvae were used in this study after the results of trial experiments showed the larvae to be more efficient in biodegrading FS than 6-day old larvae.

2.4 Characterization of faecal sludge and frass

In order to determine the suitability of FS as feedstock for BSFL as well as the suitability of the frass. he collected FS samples and the frass were analyzed for relevant physicochemical parameter. These parameters include: temperature, total solids (TS), electro-conductivity (EC), chemical oxygen demand (COD), total nitrogen (TN), phosphates, helminth eggs and heavy metals, such as copper (Cu), zinc (Zn), manganese (Mn), chromium (Cr), lead (Pb) and mercury (Hg). The values were compared with literature to examine if they fall within the range suitable for rearing BSFL. Moisture content was analyzed using gravimetric method, where a known mass of FS sample was heated in an oven at 105°C till it attained constant weight. The change in weight was then taken as a fraction of the initial wet sample volume (APHA-AWWWA-WEF, 2012). TS concentration was determined using gravimetric method by weighing an oven dried FS sample at 105°C till constant weight (24 h) and dividing by the measured volume of wet sample, expressed as g/L. Chemical Oxygen Demand (COD) was determined using closed reflux colorimetric method (APHA-AWWWA-WEF, 2012). Ammonium nitrogen (NH_4^+ -N) was determined using titrimetric method,

TABLE 1 Description of feeding rate and larval density used in experiment.

Feeding rate of FS (mg/larvae/day)	25			50			100			200		
Number of larvae (n)	100	200	400	100	200	400	100	200	400	100	200	400
Larval density (Larvae/cm^2)	0.67	1.33	2.67	0.67	1.33	2.67	0.67	1.33	2.67	0.67	1.33	2.67
FS quantity added to each box in (g)	25	50	100	50	100	200	100	200	400	200	400	800

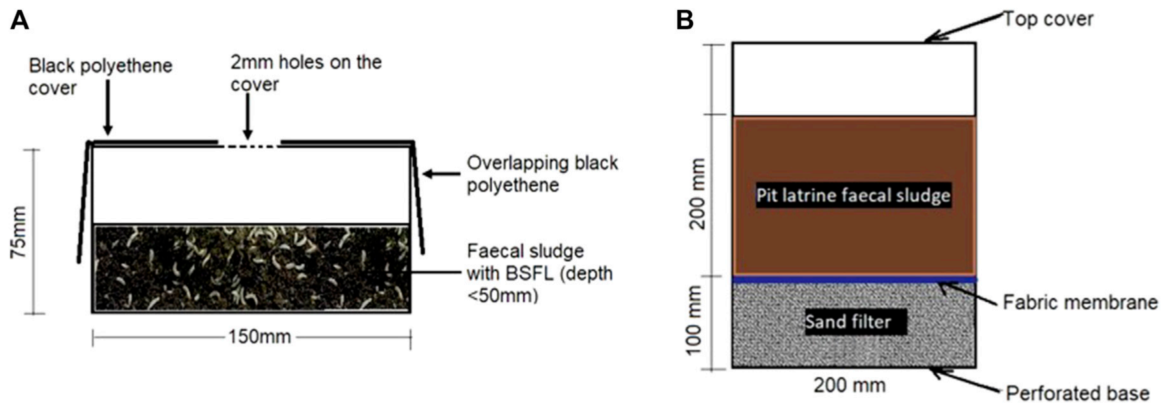


FIGURE 1
Experimental set up for: **(A)** feeding of black soldier fly larvae on faecal sludge from pit latrines; and **(B)** Dewatering of pit latrine faecal sludge using a locally made sand filter.

where samples were preliminarily distilled and then titrated with 0.002 NH_2SO_4 (APHA-AWWWA-WEF, 2012). Total Nitrogen (TN) was determined using Kjeldahl method where the samples was first digested in sulfuric acid (H_2SO_4) at 380 °C, followed by addition of excess sodium hydroxide solution. After this, they were distilled by passing them through boric solution and then back titrated using sodium hydroxide solution (Okalebo et al., 2002). Total phosphorous (TP) was determined using persulfate digestion using ascorbic acid.

Heavy metals (Cu, Mn, Zn, Cd, Cr, Pb, and Hg) were determined by atomic absorption spectroscopy (APHA-AWWWA-WEF, 2012). These metals were selected because they are metals which have the potential to harm soil organisms, plants, and animals through their entry into the food chain. This is due to the fact that the residue left after BSFL treatment can be used as soil conditioner and the prepupae as animal feed. The samples used for determining heavy metals were oven dried for 24 hr at 105°C, ground, sieved through 0.053 μm sieve and then digested with aqua regia solution. The resultant solutions were made to 50 mL by volume and aspirated using atomic absorption spectrophotometer (Agilent MY17180002 200 Series AA).

The number of helminth eggs was determined by examining them microscopically (Moodley et al., 2008). Each species of helminth eggs was enumerated separately and reported as total counts per gram of wet FS but the viability was not examined. Helminth eggs were selected because they are considered a very strong indicators for assessing health risks of BSFL due to their comparably long survival time and difficult elimination. Each parameter was analyzed for in triplicates.

2.5 Optimal feeding rate and larval density for black soldier fly larvae

In determining the optimum feeding rate and larval density, one factor experiments were carried out. The daily feeding rates of 25, 50, 100, and 200 mg/larva and larval density of 0.67, 1.33, and 2.67 larvae/cm^2 were used. These were selected basing on results of previous research (Fatchurochim et al., 1989; Diener et al., 2011; Banks et al., 2014; Nyakeri et al.,. 2019). The required quantity of FS in each container was prepared and measured using a weighing scale with accuracy of 0.1 g. The required quantity of feed to be added was calculated using the daily feeding rates, the number of larvae and a time period of 10 days, long enough to change to prepupae (Table 1). Feeding was carried out only once at the beginning of the experiment, since previous research has shown that feeding BSFL with a single lump amount of biomass leads to larger larvae and prepupae as well as microbial inactivation than feeding incrementally (Banks, et al., 2014; Lopes et al., 2020). In order to determine the impact of using BSFL for treating FS, controls were made for all treatment groups using equal quantities of FS without larvae.

The experiments were conducted in plastic containers of dimension 150 × 100 × 75 mm (Length x width x height) (Figure 1A). The depth of the feedstock in the container was maintained at 50 mm. A black polyethylene bag was placed between the box and lid to prevent oviposition by other flies and aid in darkening the interior container to avoid light interfering with BSFL feeding, since they dislike light. Tiny holes of 2 mm diameter were made on top (through the polyethylene) to allow air circulation. Air circulation is required to keep the waste temperature constant and

TABLE 2 Characteristics of FS from lined and unlined pit latrines in urban slums.

FS parameter	Unit	Lined pit latrine (n = 12)		Unlined pit latrine (n = 12)			Condition suitable for breeding BSFL
		Mean	Standard error	Mean	Standard error	*p*-value	
Temperature	°C	24.0	0.12	23.1	0.1	0.002*	10–40
pH		7.4	0.04	7.8	0.2	0.035*	5.25–8.94
Moisture content	%	90.2	0.15	81.4	0.4	0.000*	40–90
Total solid	g/L	128.6	8.51	344.8	79.4	0.010*	133–480
COD	mg/L	90,667	1244.00	90,400	435	0.844	50,000–150,000
Ammonium nitrogen	mg/L	90.3	0.33	240.0	2.50	0.000*	45–283
Total nitrogen	mg/L	2009	31.00	2746.0	34.0	0.000*	NA
Total phosphate	mg/L	1605	27.00	2063.0	57.0	0.000*	NA
Helminth eggs	No. per g	250	6.00	212.0	8.0	0.000*	NA
Copper	mg/L	84.6	0.53	38.2	0.26	0.000*	NA
Manganese	mg/L	32.3	0.27	37.6	0.32	0.000*	NA
Zinc	mg/L	414.6	3.75	190.8	3.12	0.020*	NA
Cadmium	mg/L	1.2	0.13	1.8	0.11	0.001*	NA
Chromium	mg/L	5.2	0.51	10.2	0.23	0.576	NA
Lead	mg/L	31.6	0.83	32.5	0.85	0.002*	NA
Mercury	mg/L	0.0	0.00	0.1	0.0	0.035*	NA

Note: *significant difference between FS, from lined and unlined pit latrine at $p \leq 0.05$ using independent samples *t*-test.

within the suitable range (25°C–30°C) for effective treatment of FS with BSFL (Pang et al., 2020). The experimental setup was on a raised platform and was protected from rain and direct sunlight using a tarpaulin. The experiment was run and closely monitored under ambient temperature conditions until 50% of the larvae reached prepupae stage, indicated by change of color from white to dark brown (Diener et al., 2011; Banks et al., 2014). The experiments were carried out as one factor experiments wherebt.

To examine the sole effect of degradation by BSFL, control experiments of FS from lined and unlined pit latrines were set up under similar conditions but without BSFL. After the experimental run, the prepupae were separated from the residue and the weight of each residue was measured using a weighing scale. The faecal sludge reduction (FSR) was then computed using Equation 1 (Beesigamukama et al., 2021).

$$\% FSR = \left(\frac{Initial\ weight - Final\ weight}{Initial\ weight}\right) X100 \tag{1}$$

2.6 Determination of optimal moisture content

The highest feeding rate and larval density in the previous experiments (Section 2.5) were subsequently used for determining optimal FS moisture content required by BSFL to efficiently reduce FS. Moisture content (MC) was varied by dewatering FS to 60% moisture content using a prefabricated sand filter. The 60% moisture content dewatered FS was later divided into three samples out of which two samples were rehydrated to 70%, and 80% moisture content. The moisture content ranges were selected based on the results of previous research on the effect of moisture content on BSFL survival, development time, and dry adult weight (Fatchurochim et al., 1989; Banks et al., 2014). To prevent the sand from mixing with FS, two layers of fabric mesh having about 2 mm opening were placed on top of the sand bed to separate FS from the sand (Figure 1B). The filtered water was collected inside a container placed below the filter and disposed of inside pit latrine.

The approach used in this study, *ex-situ* treatment, was preferred to *in situ* treatment (application of BSFL inside pit latrine) system due to the context of the study area. The area has high water table and is prone to flooding which make it very difficult to implement *in situ* treatment of FS by BSFL. Therefore, the study was geared towards reflecting conditions under decentralized FS treatment system, which is the most suitable option for such area, where FS is first emptied using most appropriate technology and then treated with BSFL.

2.8 Data analysis

Data analysis was carried out using Microsoft Excel 2010and Statistical Package for Social Sciences (SPSS) version 25.0 for Windows. Descriptive statistics (means and standard deviation) was used to describe the properties of FS from lined and unlined pit latrines. Independent sample *t*-test was used in investigating the differences in the mean values of the properties of lined and unlined

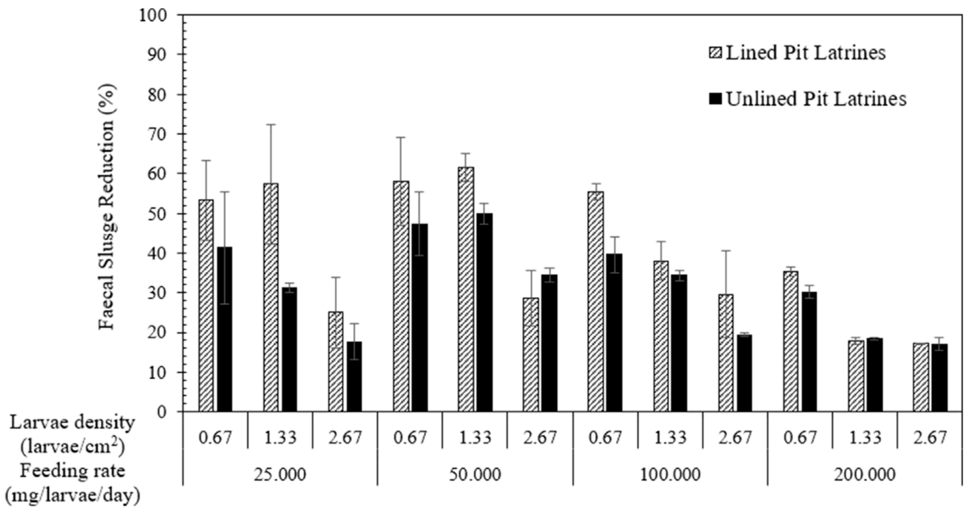


FIGURE 2
Percentage of faecal sludge reduction (FSR) with feeding rate (FR) and larvae density (LD) for FS from lined and unlined pit latrines.

pit latrines. It was also used to assess the differences between the properties of residue from both lined and unlined pit latrines and their corresponding control groups. The confidence interval used was 95%. Before analysis, all data were tested for normality and homogeneity of variance using the Shapiro-Wilk test and Levene's test in SPSS.

3 Results and discussion

3.1 Pit latrine FS characteristics and suitability in breeding BSFL

3.1.1 General pit latrine FS characteristics

The values of measured physico-chemical properties of FS from lined pit latrines are significantly different from those of FS from unlined pit latrines (p <0.05) except for COD (p = 0.844) and chromium (p = 0.576) (Table 2). Generally, the concentrations of heavy metals were higher in FS from unlined than lined pit latrines. However, some elements such as copper and zinc had higher concentration in lined than unlined pit latrines. The results also showed that FS from lined pit latrines had significantly higher helminth eggs per gram than unlined pit latrines.

Generally, the measured characteristics of FS is comparable to those found in previous studies within Kampala (Uganda) and other countries such as South Africa and Ghana (Banks et al., 2014; Chiposa et al., 2017; Semiyaga et al., 2017). However, the measured variation in characteristics between lined and unlined pit latrine FS can be attributed to the differences in the pit design, FS storage duration and toilet usage (Niwagaba et al., 2014). High moisture content from lined pit latrines FS can result from users disposing wastewater and grey water inside the pit latrines (Nakagiri et al., 2015). Unlike in unlined pit latrines, the lined wall of the latrines reduces exfiltration into the surrounding soils and hence wastewater and greywater disposed into the pit contribute to the higher moisture content observed in lined than unlined pit latrines.

The ratio of COD to TS was higher in lined than unlined pit latrines (733 and 262, respectively); hence, FS from lined pits contain more organic matter than FS from unlined pit latrines. This is vital when considering implementation of BSFL in a decentralized FS treatment plant as increase in organic content results in increase in FSR efficiency (Banks et al., 2014). The presence of heavy metals in FS from both lined and unlined latrines could have resulted from contamination due to large quantities of garbage (metallic building materials, cosmetic tins, detergents and paint tins) observed in most of the pit latrines. Studies on FS management in low income areas revealed that users of public toilets dispose solid wastes which contain metal compounds into the pit (Chiposa et al., 2017). High concentration of some metals such as copper and zinc in pit latrines could have also resulted from disposal of wastes which contain petrochemicals, contain cosmetics and leaching from solid waste damping sites since the study area has a lot of uncontrolled solid waste dumping (Tervahauta et al., 2014; Twinomucunguzi et al., 2022). The presence of lead (Pb) in the sludge could be as a result of disposal of materials such as lead-acid batteries, rubber and plastics into the pits (Appiah-Effah et al., 2014). The presence of heavy metals in FS has an impact on the use to which as they can accumulate in the larvae and prepupae of black soldier flies and consequently in the food chain (Attiogbe et al., 2019).

3.1.2 Suitability of pit latrine FS in breeding BSFL

The temperature (23°C–24°C), pH (7–8), TS (128.6–344.8 mg/L), COD (90,400–90,667 mg/L) and ammonia nitrogen (90–240 mg/L) of FS from both lined and unlined pit latrines are within the ranges suitable for effective decomposition by BSFL (temperature, 25°C–30°C (Shumo et al., 2019); pH, 6–10 (Ma et al., 2018); moisture content, 70–80% (Bortolini et al., 2020) (Table 2). These values indicate that FS from both lined and unlined pit latrines can be used to feed BSFL (Popa and Green, 2012; Lalander et al., 2013; Banks et al., 2014). Optimum feeding rate and larval density for FS from lined and unlined pit latrines.

Generally, for FS from both lined and unlined pit latrines, FSR tends to reduce with increase in larvae density (Figure 2). Highest FSR for FS from both lined (62% ± 3.5) and unlined pit latrines (50% ± 2.6) occurred at feeding rate of 50mg/larva/day and density of 1.33larva/cm^2 (Figure 2).

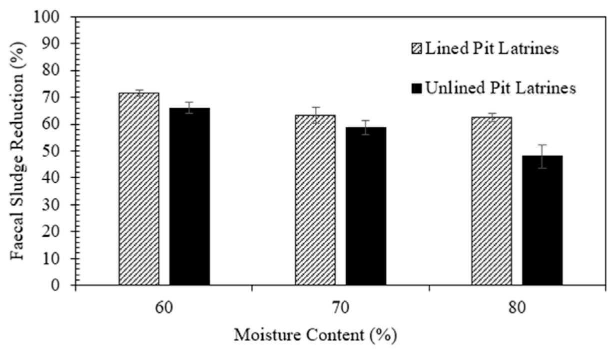


FIGURE 3
Faecal sludge reduction (FSR) ar different moisture content of both lined and unlined pit latrines.

Application of BSFL considerably reduced FS of pit latrines in volumes similar to those reported for other feedstocks: human faeces, 39.1–48.6% (Gold et al., 2020); food waste, 55.3 ± 4.1; fruit and vegetable waste, 46.7–60% (Giannetto et al., 2019). Optimum feeding rate of 50mg/larvae/day obtained in this study corresponds to previous findings by Fatchurochim et al. (1989), Banks et al. (2014) and Attiogbe et al., 2019. However, the highest larvae density of 200 (1.33larva/cm^2) is different from 400 larvae density previously reported by Banks et al. (2014). The results of the study also contradicts with the study of Diener et al. (2009) on reduction of municipal organic wastes using BSFL where 200 larvae density and 6-day old larvae had optimum decomposition at feeding rate of 100mg/larvae/day. Also, the study on dairy manure by Meyers et al. (2008) showed that use of two larvae/cm^2 density and 4-day old larvae at a feeding rate of 90mg/larvae/day resulted in maximum dry matter mass reduction of 58%. The aforementioned results imply that the reduction efficiency of biomass by BSFL depend on the interaction between factors, for example, effect of larval density is dependent on feeding rate (Parra Paz et al., 2015).

The highest FS reduction of 62% and 50% recorded in lined and unlined pit latrines, respectively, is within the range of 39–56% reported for cow manure and 50% for chicken manure (Sheppard et al., 1994; Diener et al., 2009), close to 57.5% reduction recorded by Banks et al. (2014), 65.3% recorded by Attiogbe et al. (2019) and 55.1% recorded by Lalander et al. (2014).

3.2 Moisture content variation and efficiency of BSFL in reducing faecal sludge

Generally, FSR decreased as moisture content increased from 60–80% (Figure 3). Also, at each moisture content, a higher FSR was recorded in FS from lined than unlined pit latrines; however, the differences were only statistically significant at 80% moisture content.

The reduction in FS with increase in moisture content can be attributed to lower evaporation rate for wetter FS. In addition, the fact that low moisture content favors microbial degradation of substrate (FS) to CO_2 resulting in efficient conversion of assimilated substrate into larval biomass (Bekker et al., 2021). The highest FSR was recorded at 60% moisture content in both FS types with reduction of 72 and 66% for lined and unlined pit latrines, respectively. Also, it is noted that even at high moisture content (70–80%), the FSR is still high. This implies that at highest larval density and feeding rate, BSFL can greatly reduce FS over a wider range of moisture due to high FS reduction recorded at both 70% and 80% moisture content in both types of FS (Figure 3). FSR of 50% obtained for FS from lined pit latrines at 90% moisture content when highest larval density and feeding rate is used confirms the ability of BSFL to reduce FS over a wide range of moisture content. This is advantageous in decentralized FSM since it allows FS with wide range of moisture content to be managed by BSFL, reducing the need for the dewatering stage.

The optimum moisture content of 60% obtained in this study is less than the 75% determined in the study by Banks et al. (2014) but is comparable to previous studies by Fatchurochim et al. (1989) where BSFL efficiently decomposed manure at moisture content ranging from 40 to 60%. Similar results were obtained in the studies by Diener et al. (2011) and Myers et al. (2008), where organic waste and chicken manure, respectively, were reduced efficiently at 60% moisture content by BSFL. This suggests that optimum moisture content of 60% obtained in this study is a value that can be applied for the treatment of different kinds of waste by BSFL. This moisture content value is also suitable for processing and quality of residue obtained after treatment with BSFL.

3.3 Characterization of the resulting residue

BSFL application resulted in significant differences (p <0.05) between some of the characteristics of the residue from both lined and unlined pit latrines and their corresponding control groups (Table 3). When FS from both lined and unlined pit latrines are compared to their corresponding control groups, it can be observed that there is significantly lower (p <0.05) COD concentration while ammonia nitrogen, total nitrogen and pH significantly increased (p < 0.05). There are no significant differences in moisture content, total phosphate, and helminth egg concentration between FS from both lined and unlined latrines and their corresponding control groups. However, significant difference (p = 0.000) was observed between the TS concentration in residue for FS from unlined pit latrine and its control group. There were no significant differences observed between the TS concentration in residue from FS for lined pit latrine and its corresponding control group (p = 0.399) (Table 3). Also, there was significant increase in the heavy metal concentration in the residues with BSFL in FS from both latrine types compared to the control, except mercury and lead which showed only significant differences in lined pit latrines (Table 3).

The lower COD levels in the residue when compared to the control can be attributed to the fact that BSFL accelerates decomposition of organic matter. The acceleration may be due to the respiratory action of micro-organisms in the intestine of BSFL as noted by Rehman et al. (2017). Substrates are degraded and homogenized by BSFL through muscular activities leading to surface increases for microbial action and reduction of organic matter (Prakash and Karmegam, 2010). The higher ammonia nitrogen content in the residue can be attributed to the fact that as decomposition occurs, a fraction of organic nitrogen in the influent material is transformed into ammonia. The higher ammonia nitrogen concentration in the residue also implies that the residue has higher fertilizer value than the control (Lalander et al., 2015). BSFL application resulted in significant pH increase (p <0.05) for both lined and unlined latrine FS residues, which is in line

TABLE 3 Characteristics of the residues of faecal sludge from lined and unlined pit latrines after BSFL treatment.

Physiochemical parameters	Unit	Lined pit latrine (n = 12)					Unlined pit latrine (n = 12)					Limit for use in composting
		BSFL present		Control lined			BSFL present		Control unlined			
		Mean	Standard error	Mean	Standard error	*p*-Value	Mean	Standard error	Mean	Standard error	*p*-Value	
Temperature	0C	23.70	0.115	23.27	0.120	0.060	23.03	0.2	23.50	0.115	0.049	–
pH		8.54	0.037	8.10	0.036	0.001	8.43	0.1	8.04	0.042	0.005	6–8.5
Moisture content	%	59.40	0.110	59.55	0.105	0.000	58.67	0.9	58.77	0.419	0.893	40–60
Total solid	g/g	0.497	0.0	0.697	0.0	0.399	0.539	0.0	0.853	0.0	0.000	–
COD	mg/g	92.800	0.1	99.967	0.1	0.000	88.433	0.1	96.367	0.2	0.000	>0.400
Ammonium nitrogen	mg/g	0.247	0.0	0.161	0.0	0.000	0.479	0.0	0.348	0.0	0.000	–
Total nitrogen	mg/g	1.799	0.0	1.668	0.0	0.000	1.897	0.0	1.712	0.0	0.000	0.5–4%
Total phosphate	mg/g	2.138	0.1	2.183	0.1	0.497	2.205	0.0	2.203	0.0	0.828	0.5–1.5%
Helminth eggs	No. per g	27	3	16	2	0.060	22	1.0	23	0.6	0.126	1
Copper	mg/g	0.153	0.0	0.118	0.0	0.000	0.050	0.0	0.081	0.0	0.001	0.070–0.600
Manganese	mg/g	0.425	0.0	0.493	0.0	0.000	0.409	0.0	0.453	0.0	0.001	
Zinc	mg/g	0.337	0.0	0.538	0.0	0.000	0.250	0.0	0.186	0.0	0.000	0.210–4.000
Cadmium	mg/g	0.003	0.0	0.002	0.0	0.001	0.001	0.0	0.002	0.0	0.008	0.000–0.010
Chromium	mg/g	0.032	0.0	0.028	0.0	0.026	0.036	0.0	0.035	0.0	0.009	0.070–0.200
Lead	mg/g	0.051	0.0	0.034	0.0	0.001	0.042	0.0	0.043	0.0	0.802	0.070–1.000
Mercury	mg/g	0.000	0.0	0.000	0.0	0.477	0.000	0.0	0.000	0.0	0.349	0.000–0.010

Note: significant difference between FS, from lined and unlined pit latrine and their corresponding control groups occur at $p \leq 0.05$ using independent samples *t*-test.

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with previous studies (Popa and Green, 2012; Lalander et al., 2013; Banks et al., 2014). The increase in pH for the residue can be explained by the fact that ammonia is produced from organic nitrogen during decomposition while in the liquid, ammonia acquires hydrogen ions from the water to produce hydroxide and ammonium ions; the hydroxide ions leads to increase in pH (Lalander et al., 2014). In addition, it was noted that there was no significant reduction in the amount of helminth eggs in the residue with and without BSFL. A similar finding was also reported by Lalander et al. (2014) who noted that BSFL did not have impact on reduction of helminths egg content. However, BSFL has been reported to be effective in removing *E. coli* and *salmonella* (Siddiqui et al., 2022). Since the persistence of helminth eggs presents high risk to workers using the residue, there is need for further treatment of residue prior to use.

In relation to the application of the residue as compost in agriculture, all the characteristics of the residue are within the acceptable limit, except for helminth eggs. Based on WHO guideline, the viable helminth eggs content of the finished compost product must not exceed 1 egg count per gram (WHO, 2006), but this study registered exceedingly 27 and 22 counts per gram for FS residue from lined and unlined pit latrines, respectively. In addition, the pH of the residue (8.34–8.54) is within the range suitable for optimum plant growth (7.0–8.5) (Surendra et al., 2020). This implies that the residue requires further treatment before application in agriculture.

4 Conclusion

This study has shown that BSFL can reduce FS volume from both lined and unlined pit latrines by about 60–72% under best conditions. This implies that BSFL can be used in effectively treating FS from pit latrines irrespective of lining conditions. In addition, the high removal efficiency means that it can be incorporated with other less biodegradable feedstock (i.e., brewery waste) for co-digestion by BSFL to achieve stable decomposition.

From this study, it was noted that under best conditions, FS from pit latrine with moisture content as high as 90% can be effectively treated with BSFL; reduction efficiency of 50% was obtained in the study. This indicates that BSFL can be applied in the treatment of FS from informal settlements without need for a prior dewatering step. This reduces the cost associated with processing and treatment of FS and this extra cost can be applied to other parts of faecal sludge management chain.

The properties of the residue obtained in this study shows the suitability for application as compost in agricultural fields. Also, the results of the study show that the residue contains micronutrients (zinc and copper) which are either non detected or in small amount for organic compost. Thus, addition of the residue to agricultural fields will supply the soil with micronutrients needed for its physiological and metabolic processes.

This study showed that employing BSFL for FS treatment can significantly reduce the FS volume and also produce residue of good quality. Hence, the BSFL can be used as a high-efficiency transformation agent for converting FS into stable compost especially in developing countries, where adopting technical devices for composting can be expensive and difficult to manipulate. However, there are still some unanswered questions which provide basis for future research in the following areas:

- There is need for more studies to determine how the age of larvae influences its ability to effectively decompose FS.
- The highest dose of residue to be applied to the soil needs to be determined as excess application can have adverse effect on plants.
- Since the residue odour may adversely affect its use, there is a need to investigate the odour control methods in the BSF treatment process.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

RT: Conceptualization; methodology; formal analysis; investigation; resources; writing-original draft preparation; visualization; SS: Conceptualization; methodology; formal analysis; investigation; resources; writing-original draft preparation; visualization; and supervisiosn. CN: Formal analysis; investigation; writing-review and editing; visualization; and supervision. AN: Formal analysis; investigation; writing-review and editing; visualization. JS: Formal Analysis; investigation; writing-review and editing; visualization. CM: Formal analysis; investigation; writing-review and editing; visualization. MM: Conceptualization; Methodology; Investigation; Resources; Formal Analysis; Writing-Review and Editing and Supervision. All authors read and approved the final manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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