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Processing of human faeces by wet vermifiltration for improved on-site sanitation

C. Furlong[1]

Department of Civil and Environmental Engineering, Imperial College London, London, SW7 2AZ, UK.

Email: claire.furlong@ymail.com

M.R. Templeton[1]

Department of Civil and Environmental Engineering, Imperial College London, London, SW7 2AZ, UK.

Email: m.templeton@imperial.ac.uk

W.T. Gibson[2]

[2]Bear Valley Ventures Limited, Braeside, Utkinton Lane, Cotebrook, Tarporley, Cheshire, CW6 0JH UK

Email: waltergibson@bearvalleyventures.com

Abstract

The use of a vermifilter containing *Eisenia fetida* to degrade human faeces in a continuous wet system was explored. This paper aimed to understand the formation of vermicompost within the system, the quality of the effluent produced, and the effect of different bedding matrices. Eight filters were constructed, utilising four different bedding materials: four of these systems were seeded with 400 g of worms (vermifilters) while the others served as controls. The systems were flushed with 12 litres of water per day and the experiment was split into five phases, each with different feeding regimes. Between 23.7 and 24.7 kg of fresh

[1] Corresponding author

human faecal matter was added to the vermifilters over the 360 day period. The presence of the worms was found to increase the faecal reduction to 96% in the vermifilters on average, compared to 38% in control systems on average. Statistically significant reductions in phosphate, COD and thermotolerant coliforms were achieved in the effluent of all vermifilters. The most suitable bedding matrix was a mixture of coir and woodchip. This study shows that there is potential for continuous treatment of human faeces using wet, on-site vermifilters.

Keywords: *Eisenia fetida*, sewage, vermicompost, vermifilter, vermireactor, worm

Introduction

The majority of the world's population relies on on-site, decentralised sanitation systems such as pit latrines, cesspits, and septic tanks. One of the major problems associated with these systems is that they require emptying, which can be costly, inconvenient and hazardous. In high-density urban areas these problem are amplified, due to the lack of available space. Emptying should ideally be undertaken by a vacuum pump truck, but tankers cannot gain access to narrow streets and alleys (Thye et al., 2011). Alternative small-scale emptying solutions have been developed to overcome these problems, e.g. the Gulper, MAPET (Thye et al., 2011), but these technologies are still being trialled and may not be effective for all sludge types. Worldwide approximately 200 million latrines and septic tanks must be manually emptied each year by workers descending into the pit equipped with buckets and spades (Thye et al., 2011). Furthermore, the final disposal of faecal sludge by any of these methods is often simply by dumping into the immediate environment. This reintroduces pathogens into the environment which were previously safely contained in the pit or tank. An improved on-site sanitation solution needs to be identified which reduces the frequency of required emptying of latrines, ideally together with achieving treatment of the waste so that handling and disposal of the waste are safer activities.

An on-site worm-based system may be a solution to these problems. With this approach the amount of solids within the system can potentially be reduced, due to the net loss of biomass and energy when the food chain is extended by using worms. By reducing both the frequency of emptying and the size of the system, this approach could be particularly suitable for highly dense urban and peri-urban areas. Additionally worms are known to remove pathogens (from sewage sludge) to the level where the waste can be safely applied to land (Eastman et al., 2001), and the waste produced is dry compost (known as vermicompost) rather than a sludge,

which makes it easier to handle and transport.

In the field of sanitation research, studies using *Eisenia fetida* have concentrated on the stabilisation of sewage sludge (Parvaresh et al., 2004), dried or pre-treated faecal matter (Yadav et al., 2010;Yadav et al., 2011), or wastewater mixed with organic bulking agents (Taylor et al., 2004). Pre-treatment was thought to be required as *E. fetida* died within an hour of being introduced to fresh human faecal matter (Yadav et al., 2010). The importance of the bedding layer, i.e. the matrix in which the worms live, was also noted, as they found that *E.fetida* died when fed with human faeces without this support layer (Yadav et al., 2010).

Larger scale community worm-based systems have been trialled in China for the treatment of sludge (Xing et al., 2011; Zhao et al., 2010) and sewage (Xing et al., 2010; Wang et al., 2012). Commercial on-site systems are currently available, e.g. the Solid Waste Digester (Simple Wastewater Solutions, 2010) and Biolytix™ (Biolytix, 2008), which are seeded with worms and are attached to flushing systems. They are designed for use in rural locations in developed countries but are cost-prohibitive for households in developing countries. They also have large footprints for installation in an urban context and designed for waste containing higher liquid content than is typical in developing countries.

Flushing systems are highly desirable in low-income urban and peri-urban contexts where people strive for modernity. The advantages of systems with a water trap/seal include the separation from one's own and others' waste, and the elimination of odours and flies, which add to the desirability of flushing systems. This research was a part of a larger project which used a people-led approach to sanitation improvement; therefore, in the light of these desired benefits, the study focuses on flushing systems only. No other studies have investigated wet

(flushed with water periodically) worm-based systems for degrading fresh human faeces: as such, experimental data were required to assess the feasibility of this approach for on-site sanitation in developing countries.

The specific objectives of this work were to establish whether worms can continuously (the systems are fed daily) degrade fresh human faeces under water-flushing conditions. To the best of our knowledge all other laboratory based studies have been batch fed (fed weekly). The system in the paper is described as 'wet' or 'water-flushed' whereas in traditional worm-based systems water is only added to keep the system moist (e.g. Yadav et al., 2011) or a wet slurry or sludge is added to the system (e.g. Xing et al., 2011), but no other studies have been identified in which water was flushed through the systems to simulate the conditions in a flushing sanitation system. Furthermore, this study was performed in order to determine where and how much vermicompost is deposited and to assess the quality of the effluent produced. Additionally, the effect of different bedding matrices on faecal solids reduction (mass) and effluent quality was considered. The experiments were designed to replicate a potential on-site wet worm based sanitation system, i.e. they were fed daily with fresh human faeces and water was pumped into the filters to simulate flushing a toilet.

Methodology

Experimental systems

Eight filter systems were constructed from polypropylene boxes with internal dimensions of L 37 x W 27 x H 25.5 cm and a surface area of 0.1 m^2 (Figure 1). The base of each box (except the sump box) was removed and replaced by plastic mesh with a 5 mm aperture and a further mesh with a 1 mm aperture was placed on the bedding box mesh. Each unit consisted of three boxes stacked on top of each other: the top box contained a 10 cm depth of bedding

matrices, the middle contained drainage media (plastic drainage coil with a 60 mm external diameter, cut into 60 mm segments), and the bottom box was the sump which had a tap that drained to a collection vessel. All components of the system were weighed separately to allow for changes in mass to be calculated over time.

Four different bedding matrices were tested: coir (Fertile Fibres Ltd, Withington, UK), woodchip (sourced from the Centre for Alternative Technology (CAT), Powys, Wales, UK), a volumetric mixture of coir and woodchip (50:50), and a volumetric mixture of coir, woodchip and vermicompost (33:33:33). Eight boxes were initially set up (two of each bedding matrix type), with 400 g of *E. fetida* (worm density of 4 kg/m^2) being added to one of each matrix type (vermifilter), and the second corresponding box being used as a control (did not contain worms). This worm density was selected from the estimation that 0.1 m^2 of vermifilter surface area could treat the waste from one person per day (approximately 200 g of faeces, unpublished data) and a conservative estimate of worm feed consumption of 0.5 kg feed/kg worm per day.

On top of the bedding a plastic mesh insert was placed and faecal matter was introduced on top of this mesh (the faecal mesh, Figure 1). Each system was topped with a lid which contained 40 1-mm randomly placed ventilation holes and an inlet for water additions. Water was introduced using a peristaltic pump (Watson Marlow 502S, Cheltenham, UK) to simulate flushing: approximately 12 litres of water was added during five watering periods spaced throughout the day. This happened throughout the study apart from the resting period (Phase 4) when feeding was suspended to assess the ability of digestion to go to completion during which only one litre of water was added per day to keep the systems moist.

Human faeces were collected daily from a series of bucket toilets at CAT. They were homogenised through pooling and thoroughly mixed. Once a day the specified amount of fresh faeces (Table 1) was placed on the faecal mesh. The variation in the expected feeding regime (see phase descriptions in Table 1) and actual feeding regime (see mean feed addition per day, Table 1) was due to the variations in the amount of faeces harvested. The reactors were fed from Monday to Friday as it was not feasible to harvest faeces over the weekend: therefore all the feed rates quoted in Table 1 are for a 5-day period.

Once the boxes were assembled they were wetted with six litres of water and allowed to drain for one hour. The worms were then added and allowed to acclimatise for eight days without feeding. The experiment was divided into five phases (Table 1) and ran for 360 days. The reactors were housed in a heated building where the mean temperature was 22°C (Lascar EL-USB-TC, Whiteparish, UK). A Lascar thermocouple and data logger and EC-5 moisture probe (Decagon Devices Inc., Pullman, USA) were positioned in the middle of each bedding layer.

Methods of analysis

All methods were chosen so they did not disturb or destroy the systems. Additionally, they had to be undertaken under field conditions, due to the lack of standard laboratory facilities on-site at CAT.

Moisture measurements (v/v %) were taken daily using ProCheck datalogger (Decagon Devices Inc, Pullman, USA). A potting mixture calibration was used for all boxes except for those containing only woodchip, when the perlite calibration was used. The laboratory and box temperatures were measured hourly using a Lascar EL-USB-TC thermocouple. The

mass of faecal matter on the mesh above the bedding layer (faecal mesh, Figure 1) was weighed separately.

The influent and effluent were analysed approximately weekly using Hach DR/890 field testing kits (Loveland, USA) for chemical oxygen demand (Hach Method 8000), nitrate (Hach Method 8039), nitrite (Hach Method 81532), and total phosphate (Hach Method 10127). Thermotolerant coliforms were analysed using a DelAgua Kit (Guildford, UK) (Robens Centre, 2004). The effluent pH was measured using an electrode (pH703, TECPEL, Taipei, Taiwan) and settleable solids were measured using standard methods (APHA, 1992). All samples were analysed in duplicate and arithmetic mean for the samples are reported in this paper (Table 2).

Data analysis

Waste stabilisation is reported in other papers (e.g. Yadav et al., 2011; Xing et al., 2011), and this does not reflect the reduction in the mass of the waste. Mass reduction is important when assessing this technology's suitability for on-site sanitation, as it is directly related to the necessary size of the system and emptying frequency. Mass reduction was calculated (Eq.1), together with overall faecal reduction.

Equation 1: Weekly percentage faecal reduction

$((TFMA_{W1} - FMR_{W1}) / TFMA_{W1}) \times 100$

$TFMA_{W1}$ = total faecal mass added onto mesh weekly

FMR_{W1} = faecal mass remaining on mesh at the end of the week

After 360 days the vermifilters were decommissioned and the undigested faeces on the faecal

mesh, the worm population and vermicompost were separated and weighed. The control filters were decommissioned after 30 days due to the lack of overall decomposition (8-39%) and the large amount of faecal matter that accumulated (0.73-1.1 kg).

Statistical analysis of results was carried out using SPSS 12.0.1. Student's t-test was used to compare data sets. One-way ANOVA was used to compare multiple data sets using the post-hoc Tukey test. The null hypothesis of these tests was accepted if $p \geq 0.05$.

Results and discussion

Reduction of faecal matter

In Phase 1 there was a statistically significant difference in the weekly percentage faecal reduction between the filters and vermifilters for each bedding type (Student's t-test coir p=0.003; woodchip p=0.007; coir and woodchip p=0.008; coir, wood and vermicompost p=0.006), confirming that the worms were actively degrading faecal material. Within the controls, faecal reduction was higher for the filter containing vermicompost than for the other types of bedding material (percentage feed reduction at the end of Phase 1: coir 11%, woodchip 12%; coir and woodchip 11%; coir, wood and vermicompost 33%). This was probably due to the vermicompost in the bedding matrices being microbiologically active. There was no statistically significant difference between the weekly faecal reduction in the vermifilters with different bedding matrices (ANOVA $F(3,12)=1.177$, p=0.359), therefore the type of bedding did not affect the ability of the worms to consume faecal material during Phase 1. The faecal reduction dropped in the vermifilters after the feed rate was increased at the start of Phase 2 (Table 1). The systems became acclimatised to the new feeding rate after approximately six weeks when 100% reduction was achieved; this pattern was repeated at the start of Phase 5.

In Phase 1, this could be linked to the acclimatisation of the worms to the feed, sincein other studies the worms were acclimatised prior to the experiments (Yadav et al., 2011), but in subsequent phases it was more likely to be from the population adapting to the increased feed rates, as this coincides with approximately the same amount of time required for a worm to hatch and mature (Edwards & Lofty, 1997).

After approximately six months (26 weeks) vermicompost started accumulating on the faecal mesh. This made it difficult to reliably measure faecal mass reduction beyond this point. Prior to this period the mean weekly percentage faecal reduction across all vermifilters was between 86-95% (this ranged from 23 to 176%). The variation was possibly due to the mobility of the worms and their changing presence and absence on the faecal mesh. Feeding continued during Phase 5 and at the end of the 360 day period a total of between 23.7 to 24.7 kg of fresh human faeces had been added to the vermifilters. At the end of Phase 5 the amount of faeces remaining on the faecal mesh varied from 0.023-0.665 kg; the overall faecal reduction was therefore 97 to 100%

The different components of the material on the faecal mesh at the end of the experiment were separated and weighed. The highest mass of undigested faecal matter occurred in the vermifilter containing coir bedding (coir 0.66 kg; woodchip 0.03 kg; coir and woodchip 0.15 kg; coir, wood and vermicompost 0.37 kg), which suggests that the rate of faeces consumption by the worms was lower in this system. The highest mass of worms was found on the faecal mesh when the bedding was a mixture of coir and woodchip (0.66 kg), followed by the combination of coir, woodchip and vermicompost (0.47 kg), then woodchip (0.46 kg) whilst the coir bedding had the lowest mass of worms (0.28 kg). It can be inferred from this

that coir alone is a less suitable bedding material, which may be because the worms prefer to consume the coir compared to the faecal matter. Anecdotal evidence of this has been highlighted in the general vermicomposting literature (Appelhof, 1997).

The worm density increased in all vermifilters: from 4 kg/m^2 to 8.56 kg/m^2 in the coir vermifilter; to 10.10 kg/m^2 in the woodchip and coir vermifilter; to 13.19kg/m^2 in the woodchip, coir and vermicompost vermifilter and to 14.48 kg/m^2 in the woodchip vermifilter. This contradicts earlier studies (Yadav et al., 2010; Yadav et al., 2011) which found that a worm density of 4 kg/m^2 was unsustainable. The conditions within their filters and the ones reported in this paper were very different, i.e. feeding regimes, application of feed, water flow, and bedding type, all of which could affect the health of the worm population. Additionally other authors have reported increased worm density over time: Zhao et al.(2010) reported that worm density increased from 32g/L to 55.7g/L over a period of six months and Lui et al. (2012) reported a worm density increase from 32 g/L to 46.3 g/L over a seven month period. The feed in both of these studies was sewage sludge diluted with water, suggesting that higher worm densities may be sustainable in wetter systems.

Vermicompost was deposited throughout the vermifilter systems, though the majority was retained in the upper part of the system, i.e. the bedding layer and faecal mesh combined. The rate of accumulation of vermicompost over the period of the experiment was between 2.7 and 4.1 kg/year (coir 4.1 kg; woodchip 2.7 kg; coir and woodchip 4.0 kg; coir, wood and vermicompost 4.1 kg). The lower mass accumulated in the system using woodchip was probably due to the coarser filtering action of the woodchip, with vermicompost being washed through the bed. Additionally, it could be also attributed to the worms inability to convert this material into vermicompost. A higher mass of vermicompost (1.6 kg) was found

on the faecal mesh of the vermifilter containing the coir and woodchip bedding (compared to coir 0.75 kg; woodchip 1.3 kg; coir, woodchip and vermicompost 1.3 kg), because of more worms inhabiting this part of the system compared to the other vermifilters. This suggests that this layer was more active in this vermifilter because of the bedding type. A higher proportion of vermicompost was deposited or formed in the bedding layer of the coir system (2.43 kg) (compared to woodchip 0.92 kg; coir and woodchip 1.7kg; coir, woodchip and vermicompost 2.1 kg), which supports the hypothesis that the worms preferred to consume the bedding in this system rather than the faecal matter.

All of the vermifilter communities remained aerobic and healthy over the 360 days as assessed by visual and olfactory inspection. The vermifilters were fed 200 g of faecal matter on 40 days in Phase 5, which is the mean amount of faeces produced per person per day. Therefore this size of vermifilter (a surface area of 0.1 m^2) has the potential to treat the waste from one person. This would lead to a household system that is considerably smaller than traditional on-site sanitation systems such as septic tanks or pit latrines.

Effluent quality

The volume of vermicompost in the effluent during Phase 5 was measured as settleable solids, as the vermicompost was dense and settled out readily (Zhao et al., 2010). The mean settleable solids in the effluent were highest in the filter containing woodchip (4.9 ± 1.4 mL/L) compared to coir (4.0 ±1.3 mL/L), woodchip and coir (3.8 ± 1.4 mL/L) and woodchip, coir and vermicompost (3.0 ± 1.1 mL/L) as woodchip was a coarser filter, which led to more vermicompost being washed through the vermifilter. However, no statistical difference was found (ANOVA $F(3,32)=1.374$, $p=0.269$).

The pH of the influent generally increased as it passed through the vermifilter (influent mean pH 6.21, effluent mean pH 6.70). Earlier studies have also recorded this (Xing et al., 2010) and it was expected, as vermicompost is known to have a higher pH than the waste being processed by the system (Appelhof, 1997). This is thought to be due to the waste being neutralised by secretions from the worms' intestines and by the ammonia which is excreted by worms (Edwards & Lofty, 1997).

Table 2 summarises the mean quality of the influent and effluent from all the boxes. Phosphate was removed in the system, which contrasts earlier findings (Taylor et al., 2004) where phosphate levels increased because of the leaching of phosphate from the vermicompost bedding/filter media. The mean total phosphate removal was 24% in Phase 2, 47% in Phase 3 and 58% in Phase 5, with no difference in the removal rates for the different bedding types (ANOVA $F(3,28)=0.718$, $p=0.550$). A more recent study (Wang et al., 2011) supports these findings with a mean total phosphate removal of 98.4%, when lower levels of total phosphorus (5.05 to 9.88 mg/L) were present in the domestic waste water being treated (Table 2). Phosphorus removal in vermifilters has been attributed to a number of processes, including the direct absorption of phosphorus by growing cells, the enhanced storage of phosphorus as polyphosphorus by bacteria in the system and precipitation of phosphorus (Wang et al., 2011).

Nitrate levels increased as the effluent passed through the system, indicating that nitrification (conversion of ammonia to nitrate) was occurring. This has also been reported in a previous study of vermifiltration of domestic sewage (Wang et al., 2011). An earlier study (Taylor et al., 2004) reported that denitrification also occurred, but the bedding depth in that study was 50 cm which would have better created anoxic conditions than in the present study.

In Table 2 it can be seen that higher COD levels were observed during Phase 1 in the vermifilters compared to the control systems. No statistical difference was observed when paired analysis was undertaken (t-test coir p=0.02; woodchip p=0.79; woodchip and coir p=0.13; woodchip, coir and vermicompost p=0.69), except in the systems using a coir bedding matrix. This was possibly because coir is inert, coupled with its filtering capacity. As the majority of the COD is contained in the faecal matter and the bedding layer acts a filter for this material, it was hypothesised that higher COD levels would be found in the effluent in the vermifilters with coarser bedding materials. The type of bedding material did not affect the effluent quality across all phases (ANOVA F (3,80)=1.574, p=0.202). At the start of each new experimental phase when the feed level was increased, there was a general decreased in the COD removal until the system stabilised, it increased and then remained relatively constant. The mean COD removal achieved during Phase 5 (Table 2) was 86-87%, which is comparable to the 81% removal which was reported in a previous study using a multi-stage vermifilter (Wang et al., 2011). It should be noted however that the COD in the influent their study was much lower, as it was rural domestic wastewater. The system tested also had higher levels of COD removal compared to levels found in septic tanks (47%, Lowe et al., 2009) and other vermifilter pilot studies (47-58%, Zhao et al., 2010); one vermifilter study actually found that COD in the effluent increased (Taylor et al., 2003).

The thermotolerant coliform removal across all the boxes ranged from 1-log to 3-log with the mean removal being 2-log.There was no statistically difference in the removal of thermotolerant coliform bacteria across all vermifilters (ANOVA F(3,32) =1.02, p=0.399). The removal reported in this paper are higher than those obtained in a more complex full-scale worm-based (1-log to 2-log removal, Weiss & Scholes, 2007) and septic tanks (1-log

removal, Lowe 2009), although it may be that in these studies the influent was more dilute. No experimental studies have been found reporting the bacteriological effluent quality of pit latrines, possibly due to the difficulty in obtaining a sample.

Implications for on-site sanitation systems

From the data it can be seen that this technology has the potential for on-site sanitation applications. The worms have the ability to feed on fresh human faeces under flushing conditions, meaning the vermifilter can be coupled with a low volume pour-flush system, which brings the additional benefit of a water seal (although it should be noted that the vermifilter was aerobic and therefore did not smell). Additionally the system proved to be robust and the worm populations survived periods when they were not fed (Phase 4) and periods of variable feeding (Phase 5). The conversion of faeces to vermicompost in the system was between 11 and 18% by mass. Using these conversion values it can be calculated that annually faeces from 10 people (720 kg) would be converted to between 79 and 130 kg of vermicompost. This is thought to be a conservatively low estimate of the mass of the vermicompost generated, as being biologically active it is thought that it would breakdown further in the system. Furthermore, it should be noted that this system was running for almost a full year (360 days) and the vermicompost accumulation over time did not cause any blockages in the system or other practical operational problems.

Results from this paper suggest that at full scale, a system could be very compact, possibly having an area of $1m^2$ and depth of 0.9 m to serve a household of 10 people. The performance of the system in terms of solids reduction and effluent quality looks promising and potentially superior to existing options for low income families. Although the effluent quality from this system would not be high enough for direct discharge into a water courses, it is of a standard

where it could be infiltrated into the soil where it would be further treated by the *in-situ* soil microorganisms, which is the same strategy used currently with septic tanks and pit latrines in developing countries. As the system trialled in this paper was extremely simple and flexible (i.e. different materials of construction could be used) this makes it highly adaptable for use in developing countries' contexts. Additionally the worms used are found worldwide, but other local species could be trialled.

Conclusions

This study was undertaken to test the feasibility of a wet vermifilter for processing fresh human faeces. The presence of the worms increased the faecal reduction rates compared to the control systems. The effluent quality from these simple vermifilter was found to be higher than from septic tanks, and other vermifilter systems. A surprising finding from this study was the high worm density that the wet system supported. The findings of this paper suggest that this technology has the potential to develop into a new type of on-site sanitation system for developing countries; because of the estimated small size of these systems, they would be particularly suited to high density urban and peri-urban areas.

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Figure Captions

Figure 1: Experimental configuration