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

C. Furlong, M. R. Templeton and W. T. Gibson

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 L 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 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 76% on average, compared to 17% in the control systems on average. Statistically signiﬁcant reductions in phosphate, chemical oxygen demand 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.

Key words | *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 problems 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, 2011), or wastewater mixed with organic bulking agents (Taylor et al. 2003). 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 (Zhao et al. 2010; Xing et al. 2011) and sewage (Xing et al. 2010; Wang et al. 2011). 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 developing countries but are cost-prohibitive for households in developing countries. They also have large footprints for installation in an urban context and are 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×W 27 ×H 25.5 cm and a surface area of 0.1 m² (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/m²) 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 m² 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 L 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 1 L 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.

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**Figure 1** | Experimental configuration.
Once the boxes were assembled they were wetted with 6 L of water and allowed to drain for 1 h. The worms were then added and allowed to acclimatise for 8 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.

#### Weekly percentage faecal reduction

$$\text{(TFMA}_W^1 - \text{FMR}_W^1) / \text{TFMA}_W^1 \times 100$$

where TFMA$_W^1$ = total faecal mass added onto mesh weekly; FMR$_W^1$ = 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 (11–33%) and the large amount of faecal matter that accumulated (0.76–1.1 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 $p \geq 0.05$.  

### Table 1 | Experimental phases

<table>
<thead>
<tr>
<th>Phase</th>
<th>Phase description</th>
<th>Period (days)</th>
<th>Water addition per day (l)</th>
<th>Mean feed addition per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50 g feed</td>
<td>1–34</td>
<td>12</td>
<td>47.8 (sd = 14.6)</td>
</tr>
<tr>
<td>2</td>
<td>100 g feed</td>
<td>35–76</td>
<td>12</td>
<td>98.9 (sd = 5.9)</td>
</tr>
<tr>
<td>3</td>
<td>150 g feed</td>
<td>77–94</td>
<td>12</td>
<td>135.4 (sd = 31.4)</td>
</tr>
<tr>
<td>4</td>
<td>Resting period</td>
<td>95–124</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>Variable feed loading</td>
<td>125–360</td>
<td>12</td>
<td>106.4 (sd = 38.2)</td>
</tr>
</tbody>
</table>

sd – standard deviation.
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 vermicompost for each bedding type (Student's t-test: coir $p = 0.005$; 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 vermicompost 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 vermicompost filters 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 6 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, since in 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 vermicomposts was between 86 and 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 and 24.7 kg of fresh human faeces had been added to the vermicomposts. 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 97–100%

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 vermicompost 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 vermicomposts: from 4 to 8.56 kg/m² in the coir vermicompost; to 10.10 kg/m² in the woodchip and coir vermicompost; to 13.19 kg/m² in the woodchip, coir and vermicompost vermicompost and to 14.48 kg/m² in the woodchip vermicompost. This contradicts earlier studies (Yadav et al. 2010, 2011), which found that a worm density of 4 kg/m² 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 32 to 55.7 g/L over a period of six months and Lui et al. (2012) reported a worm density increase from 32 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 vermicompost system, 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 vermicompost 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. This suggests that this layer was more active in this vermicompost 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 1.7 kg; 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 vermicompost communities remained aerobic and healthy over the 360 days as assessed by visual and olfactory inspection. The vermicomposts 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 vermicompost (a surface area of 0.1 m²) 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 that 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. 2005) 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 (5.05–9.88 mg/L) were present in the domestic wastewater 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. 2005) 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 chemical oxygen demand (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 $p = 0.15$; 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 as 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 decrease 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 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. 2005).

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 statistical 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 et al. 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 1 m² 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 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 vermifilters 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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