



Vermicomposting as manure management strategy for urban small-holder animal farms – Kampala case study



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ABSTRACT

Inadequate organic waste management can contribute to the spread of diseases and have negative impacts on the environment. Vermicomposting organic waste could have dual beneficial effects by generating an economically viable animal feed protein in the form of worm biomass, while alleviating the negative effects of poor organic waste management. In this study, a low-maintenance vermicomposting system was evaluated as manure and food waste management system for small-holder farmers. A vermicomposting system using the earthworm species *Eudrilus eugeniae* and treating cow manure and food waste was set up in Kampala, Uganda, and monitored for 172 days. The material degradation and protein production rates were evaluated after 63 days and at the end of the experiment. The material reduction was 45.9% and the waste-to-biomass conversion rate was 3.5% in the vermicomposting process on a total solids basis. A possible increase in the conversion rate could be achieved by increasing the frequency of worm harvesting. Vermicomposting was found to be a viable manure management method in small-scale urban animal agriculture; the return of investment was calculated to be 280% for treating the manure of a 450 kg cow. The vermicompost was not sanitised, although hygiene quality could be improved by introducing a post-stabilisation step in which no fresh material is added. The value of the animal feed protein generated in the process can act as an incentive to improve current manure management strategies.

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1. Introduction

Like many other fast-growing urban centres in the developing world, Kampala, the capital of Uganda, does not have the infrastructure nor the economic capacity to properly treat and dispose of solid waste (Lohri et al., 2013; Memon, 2010). In Kampala, an estimated 1500 tonnes of solid waste is generated every day, of which only 40% is collected and taken to landfill (OAG, 2010). The majority (92%) of the solid waste taken to landfill is organic material (Komakech et al., 2014b). At the landfill, this organic material decomposes anaerobically and produces the potent greenhouse gas methane (Eleazer et al., 1997). In Kampala there is one official landfill, which operates as an open dump, and many unofficial open dumps. Greenhouse gas emissions from open dumps have been estimated by Manfredi et al. (2009) to be 1000 kg CO₂ equivalents tonne⁻¹ waste and therefore the organic waste discarded on open dumps has a high global warming factor.

Kampala has around 4000 cows, 3000 goats, 9000 pigs and 250,000 chickens, which together generate a considerable amount of manure (Komakech et al., 2014a). Most of the manure produced (59%) is discarded in one way or another (left untouched, dumped in storm channels), while 32% is spread untreated as fertiliser (Komakech et al., 2014a). Animal manure is a known source of zoonotic pathogens (Pell, 1997) and it is thus a major risk factor for the spread of disease among both animals and humans if left untreated (Albiñ and Vinnerås, 2007). Organic waste and animal manure contain valuable plant nutrients and organic compounds that can restore degraded soils and ensure sustainable long-term agricultural activity (Diacono and Montemurro, 2010). Properly treating the organic waste fraction reduces the environmental impact by avoiding greenhouse gas emissions from landfills (Hoornweg and Bhada-Tata, 2012) and decreasing/avoiding the need for chemical fertiliser (Pimentel et al., 2005).

Over the past decades, African soil fertility has degraded to alarming levels with intensified farming (Morris et al., 2007). Henao and Baanante (2006) reported that the yearly net loss of NPK from soils in many African countries, including Uganda, is

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greater than 60 kg ha^{-1} . Organic fertilisers are important in the process of regenerating, and also maintaining, soil fertility (Diacono and Montemurro, 2010; Meng et al., 2005).

In Kampala, the demand for livestock products have increased in recent years due to urbanisation, population growth and increased income (Lumu et al., 2013). However, high quality animal feed protein is expensive and hard to find (Katongole et al., 2012).

By vermicomposting the organic waste, both these issues could be tackled. During the vermicomposting process the organic waste is converted into two valuable products: organic fertiliser (Arancon et al., 2004; Atiyeh et al., 2000) and worm biomass, which can be used as a protein source in animal feed (Mitchell, 1997). In this way, animal feed is produced directly from waste.

The most commonly used earthworm species in vermicomposting are *Eisenia feotida* and *E. andrei* (Dominguez and Edwards, 2010). Another possible species, the African night crawler (*Eudrilus eugeniae*), is a large worm that is native to the African continent (Dominguez et al., 2001). Compared to the commonly used *E. feotida*, *E. eugeniae* is larger, have a similarly high reproduction rate but has somewhat smaller tolerable temperature range; it does not survive below 12°C or above 30°C for prolonged periods (>50 days) (Viljoen and Reinecke, 1992). For Kampala, with a mean minimum temperature of 17.5°C and a mean maximum temperature of 27.9°C over the year (World Meteorological Organization, 2014), the usage of *E. eugeniae* is favourable.

The aim of this study was to evaluate the potential of vermicomposting as manure and food waste management strategy for small-holder urban animal farmers. Vermicomposting technology was selected as it has been demonstrated to efficiently reduce material volume, while at the same time generate worm biomass that can be used as animal feed protein (Ibáñez et al., 1993) and vermicompost, a valuable organic fertiliser (Garg et al., 2006). A low-maintenance vermicomposting system for the treatment of cattle manure and food waste was set up was run for 172 days, key parameters were analysed after 63 days and at the end of the experiment. Samples of the inflow material, produced vermicompost and generated worms were collected; process efficiency was evaluated and an economic assessment of the treatment potential conducted.

2. Material and methods

2.1. Vermicompost unit

The vermicomposting unit was placed at the Makerere University Agricultural Research Institute Kabanyolo (MUARIK) on the outskirts of Kampala, Uganda, and was run by research technicians at the site. The treatment unit consisted of custom-made hard-wood pallet frames – made of wood from the tree *Albizia coriaria* (local name *mugavu*), used for its anti-termite properties – that were stacked on top of each other. At the start of the experiment the unit consisted of a base pallet, a support pallet and a top pallet (Fig. 1a). With the accumulation of material in the unit, additional support pallets were added, to a maximum of three support pallets (five pallets in total). The base pallet had netting on the bottom, to prevent rodents from entering, and was filled with bedding material in the form of matured compost. The bedding material acts as a refuge for the worms when the conditions in the compost become unfavourable (e.g. high temperature or ammonia concentration (Dominguez and Edwards, 2010)). Damp newspaper balls were placed at the edges of the pallet to encourage cocoon laying, a method that had been observed to improve the rate of cocoon production in previous experiments. The top pallet was covered with netting to support banana leaves, used to block out light (Fig. 1b).

2.2. Addition of earthworms and waste to the treatment unit

Earthworms of the indigenous species *E. eugeniae*, found in manure piles, were used in the treatment unit. At the start of the experiment 1700 earthworms were placed in the bedding material and the waste added on top. The unit was top feed, i.e. fresh waste was added on top of processed waste with a feeding frequency varying between every day to every third day. After one month (day 29) another 1900 earthworms were added to the system. The unit was mainly fed three-day-old manure (around 80% of total feed added), but also food waste (around 20% of total feed added). The amount of waste added to the unit was adjusted in accordance with the amount consumed by the earthworms (Table 1). At the start of the experiment, the feeding rate was quite high ($49 \pm 10 \text{ kg}$ per week in week 5–9). It was noted that the

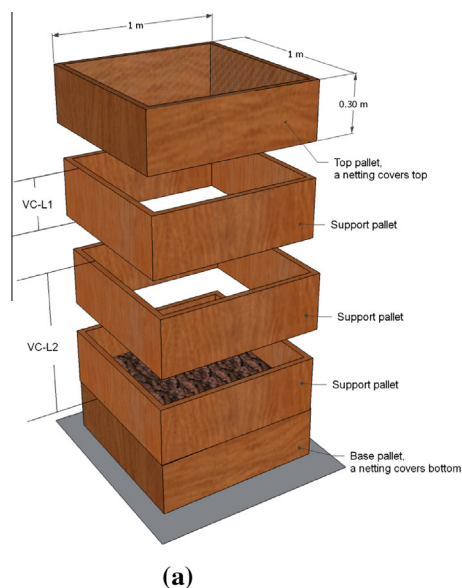


Fig. 1. Schematic representation (a) and photo (b) of the vermicompost treatment unit. The unit was made up of hard-wood pallets ($1 \times 1 \times 0.30 \text{ m}$) stacked on top of each other. The base and top pallets had a netting covering the bottom/top, the base pallet was filled with bedding material. The two levels analysed are shown in the schematic representation.

Table 1

The type and amount of waste (wet weight) added to the unit throughout the experiment.

	Manure (kg)	Food waste (kg)	Total (kg)	Manure (%)
Week 1 ^a	6.0	0.5	6.5	92.3
Week 2	5.0	7.0	12.0	41.7
Week 3	10.0	5.0	15.0	66.7
Week 4	5.6	10.5	16.1	34.8
Week 5 ^b	52.9	7.1	60.0	88.2
Week 6	32.0	15.0	47.0	68.1
Week 7	61.0	10.0	71.0	85.9
Week 8	47.0	5.0	52.0	90.4
Week 9	32.0	2.0	34.0	94.1
Week 10 ^c	5.0		5.0	100
Week 11–Week 14 ^d No feeding				
Week 15	0.9	1.1	2	45.0
Week 16	10.1	4.1	14.2	71.1
Week 17	2.1	0.9	3.0	70.0
Week 18	7.5	2.5	10.0	75.0
Week 19	9.0	5.0	14.0	64.3
Week 20	10.0	1.0	11.0	90.9
Week 21	19.3	5.3	24.6	78.5
Week 22	12.2	1.8	14.0	87.1
Week 23	20.7	3.3	24.0	86.3
Week 24	15.4	2.6	18.0	85.6
Week 25 ^e	24.9	3.1	28.0	88.9
Week 1–25	388.6	92.8	481.4	80.7

^a Addition of 1700 worms.

^b Addition of 1900 worms.

^c Removal of 4700 worms.

^d Addition of 1,700 worms.

^e Total number of worms, 15,430.

waste was not being properly processed. The feeding rate was thus reduced from week 10. In week 11 (day 63), 87% (4600 worms) of the total number of worms in the compost were harvested while 13% (700) were placed back as inoculate for the continuous process. All the worms >5 cm were counted; newly hatched worms (<5 cm) and cocoons – that according to [Reinecke and Viljoen \(1988\)](#) have an average length of 6 mm – were not included. In response to the worm harvesting, no waste was added week 11–14. On day 74, 1700 worms were added to the unit. After the resting month, the amount of waste added was gradually increased in accordance with the feeding of the worms. The final five weeks the feeding rate was 22 ± 6 kg per week.

2.3. Sampling

Samples were collected from the unit in order to verify the vermicomposting process. Microbial and physico-chemical parameters were analysed. The samples were collected from two levels, the top level (VC-L1) and the middle-bottom level (VC-L2) ([Fig. 1a](#)). The hypothesis was that the material at the lower levels of the unit would be more stabilised, as it was a vertical system and because the worms move from bottom to top. The concentration of analysed microorganisms was thus expected to be lower in the lower levels. From each level, five random grab samples of around 300 g each were collected in 500 mL plastic beakers. The samples were placed in a cooling box with cooling pads and analysed within 24 h. The worms added to the unit were counted manually at the time of addition (day 0, day 29 and day 72). The total number of worms present in the unit were counted at harvesting (day 63) and at the end of the experiment (day 172).

2.4. Physico-chemical analysis

Samples were sent to the Soil and Plant Analytical Laboratories at NARL in Kampala for analysis of total nitrogen (N), total phosphorous (P) and total potassium (K), following the procedures specified by [Okalebo et al. \(2002\)](#). Total nitrogen was analysed using

the Kjeldahl method. For total phosphorus, the dried and ground samples were digested using a mixture of nitric and sulphuric acid in a digester at 330 °C and determined using the ascorbic acid method. For potassium analysis, the samples were dried, grounded and digested using sulphuric acid at 360 °C for two hours, upon which the sample was completely oxidised and the concentration determined by spectrometry.

The material was dried at 105 °C for 14 h for determination of total solids (TS) and at 550 °C for 4 h for total volatile solids (VS).

2.5. Microbial analysis

For the microbial analyses, 1 g of material was dispersed into 9 mL buffered 0.9% NaCl peptone water with the surfactant Tween (pH 7) and further diluted to 10^{-5} of original concentration in the same buffer.

Salmonella spp. was detected by growth on plates of xylose lysine desoxycholate agar (XLD) (Oxoid AB, Sweden) containing 0.15% sodium-novobiocin. The plates were incubated at 37 °C for 24 h. To lower the detection limit to 10 CFU g^{-1} , 1 mL sample was allocated between five XLD plates in 200 μL aliquots and all salmonella-specific colonies counted.

For detection of *Enterococcus* spp., 100 μL sample was spread on plates of Slanetz–Bartley agar (Oxoid AB, Sweden) incubated at 40–41 °C for 48 h and counted with a detection limit of 100 CFU g^{-1} .

Total coliforms (TC) were enumerated in double layer agar using violet red bile agar (VRB) (Oxoid AB, Sweden); 1 mL sample was mixed with 7–8 mL agar and upon solidification of the first layer, additional 7–8 mL agar were added. The plates were incubated at 40–41 °C for 24 h and counted with a detection limit of 10 CFU^{-1} . TC are usually incubated at 37 °C, but the aim of this study was to measure the presence of thermotolerant coliforms (TTC), which are determined by incubation at 44 °C for 24 h. The temperature in the incubator exceeded 40 °C in some instances but never reached 44 °C.

2.6. Worm analysis

All worms >5 cm were enumerated. For microbial and physico-chemical analysis, the worms were washed in buffered 0.9% NaCl peptone water with 0.1% Tween 80 (pH 7) and bathed in 70% ethanol. The washed worms were weighed and crushed using a mortar and pestle. Each sample comprised 3–5 worms. The concentrations of *Salmonella* spp., *Enterococcus* spp. and TC were analysed in the worms. Predominantly adult worms were used in the analyses.

At the site, five samples of 100 randomly selected juvenile worms and one sample of 350 juvenile worms were weighed at different occasions. These worms were not washed prior to weighing.

2.7. Calculations

2.7.1. Material conversion

The total generated worm biomass (ΔWBM) was calculated as:

$$\Delta\text{WBM} = N_{\text{Harvested}}(\text{frac}_A \times m_A + \text{frac}_J \times m_J) - N_{\text{Added}} \times m_J \quad (1)$$

where N is calculated number of worms, A is adults, J is juveniles, m is the average weight and frac is the fraction of the total.

The waste-to-biomass conversion rate (BCR) of the system was calculated on a TS basis as:

$$\text{BCR} = \frac{\Delta\text{WBM}_{\text{Tot.TS}}}{\text{Waste}_{\text{Tot.TS}}} \times 100 \quad (2)$$

where $\Delta\text{WBM}_{\text{Tot.TS}}$ is the total amount of solids in the total generated worm biomass (estimated in Eq. (1)) and $\text{Waste}_{\text{Tot.TS}}$ is the total solids in the added manure and food waste.

The material reduction on a total solids basis ($Mat_{TS,Red}$) was calculated assuming that the total amount of ash in the inflow materials equals the total amount of ash in the treatment residues, described as:

$$Waste_{Tot,Ash} + WBM_{Tot,Ash,Added} = VC_{Tot,Ash} + WBM_{Tot,Ash,Harvested} \quad (3)$$

where, $Waste_{Tot,Ash}$ and $WBM_{Tot,Ash,Added}$ is the total mass of ash in the inflow waste and the added worms (i.e. the inflow materials), while $VC_{Tot,Ash}$ and $WBM_{Tot,Ash,Harvested}$ is the total mass of ash in the vermicomposted material and harvested worms (i.e. the outflow from the unit).

For the calculations, the percentage ash values for *E. eugeniae* reported by Hilton (1983) 10.5% ash on a TS basis were used. $Mat_{TS,red}$ on a TS basis was calculated as:

$$Mat_{TS,red} = \left(1 - \frac{VC_{Tot,TS}}{Waste_{Tot,TS}}\right) \times 100 \quad (4)$$

where $VC_{Tot,TS}$ and $Waste_{Tot,TS}$ is the total amount of total solids in the vermicompost and inflow waste, respectively. The total mass of the generated vermicompost was not weighed, so the total mass of vermicompost ($VC_{Tot,TS}$) was calculated as:

$$VC_{Tot,TS} = \frac{VC_{Tot,Ash}}{VC_{Ash}} \quad (5)$$

where VC_{Ash} is the ratio of ash in the vermicompost – derived from the percentage VS measured for the vermicomposted material ($VC_{Ash} = 1 - VC_{VS}$) – and $VC_{Tot,Ash}$ is the mass of the total ash in the vermicompost, calculated in Eq. (3).

The material reduction of a VS basis ($Mat_{VS,red}$) was estimated as:

$$Mat_{VS,red} = \left(1 - \frac{VC_{Tot,VS}}{Waste_{Tot,VS}}\right) \times 100 \quad (6)$$

where $VC_{Tot,VS}$ and $Waste_{Tot,VS}$ is the total amount of total volatile solids in the vermicompost and waste, respectively.

2.7.2. Mass balance

The material in the vermicompost was assumed to be mainly polysaccharides (cellulose and starch), thus the chemical formula $C_6H_{10}O_5$ was used when calculating the amount of oxygen needed for respiration. For each polysaccharide, six oxygen molecules were required for full degradation into six carbon dioxide and five water molecules. In the mass balance, it was assumed that the total mass of material reduced on a VS basis (Eq. (6)) had been completely respired into carbon dioxide and water.

2.7.3. Economic assessment

The return on investment (ROI) was calculated over a five year period on inflation compensated net present value (NPV) basis. The NPV was calculated as:

$$NPV_{t=5} = \sum_{t=5}^T \frac{C_t}{(1-i)^t} - C_0 \quad (7)$$

where C_t is the net cash inflow during the period t , t is the number of time periods, i is the inflation compensated interest rate (interest rate – inflation rate) and C_0 is the total investment cost.

The five year ROI was calculated as:

$$ROI_{t=5} = \frac{NPV_{t=5}}{C_0} \quad (8)$$

2.8. Statistical analysis

ANOVA with 95% confidence interval was used to establish whether a statistically significant difference existed between the fresh manure and the two levels, followed by Tukey post hoc test with 95% family-wise confidence level. All analyses and graphical presentations were conducted in R (R Development Core Team, 2011).

3. Results

3.1. Worm biomass flow

Juvenile worms were added three times during the first half of the experiment. Worms were harvested twice during the 172 day study (Fig. 2a). At the first harvesting (day 63) the majority (approx. 80%) of the worms were adult. By the end of the experiment (day 172), this had shifted to the majority of the worms (approx. 80%) being juvenile. In total, 5300 worms were added to the system, while 20,370 worms were found in total throughout the experiment. The average weight of an adult worm was 2.3 g, while the average juvenile worm weight was 0.8 g (Table 2). A total of 21.7 kg biomass was estimated to have been generated in the unit (Eq. (1)), yielding a waste-to-biomass conversion rate of 3.5% (Eq. (2)) on a TS basis. This value is likely to be a conservative estimate of the actual conversion rate, as the smaller worms were not included and many worms escaped from the system.

3.2. Physico-chemical changes in vermicompost

The percentage TS increased while the percentage VS decreased during the vermicomposting process (Table 3). The nitrogen (N) content in the vermicomposted material decreased significantly ($p < 0.05$), while the potassium (K) content increased significantly. The change in phosphorous (P) was small and only significant

Table 2

Mean weight of adult and juvenile worms, mean \pm SD.

	Adult ($n = 9$)	Juvenile ($n = 6$)
Weight (g)	2.28 \pm 0.23	0.80 \pm 0.08

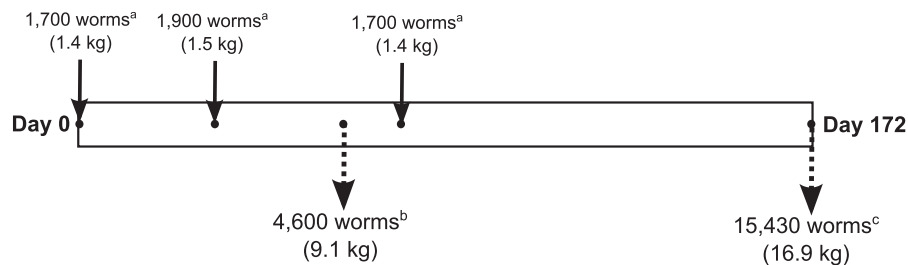


Fig. 2. The flow of biomass (addition and extraction of worms) in the unit over time (172 days): the added worms are represented by solid lines while the harvested worms are represented by dotted lines. ^aPredominantly juvenile worms; ^bpredominantly adult worms; ^c20% adult, 80% juvenile worms.

Table 3

Total solids (TS), volatile solids (VS) and N, P and K content (%) of the fresh material and the top (VC-L1) and bottom (VC-L2) levels of the vermicompost treatment unit, mean \pm SD.

	TS (%)	VS (% of TS)	N (% of TS)	P (% of TS)	K (% of TS)
Fresh	18.8 \pm 1.1	78.2 \pm 0.3	3.07 \pm 0.001	0.046 \pm 0.000	0.76 \pm 0.12
VC-L1 (n = 5)	25.5 \pm 0.8 ^{a,b}	62.2 \pm 2.4 ^a	2.55 \pm 0.049 ^a	0.052 \pm 0.003	1.02 \pm 0.00 ^a
VC-L2 (n = 5)	28.2 \pm 1.3 ^{a, b}	59.6 \pm 3.2 ^a	2.54 \pm 0.028 ^a	0.054 \pm 0.002 ^a	1.02 \pm 0.00 ^a
Worms (n = 3)	14.5 \pm 0.2	70.0 \pm 0.2 ^c	7.4 \pm 0.1		

^a Significantly ($p < 0.05$) different from fresh material.

^b Significantly ($p < 0.05$) different from VC-L1/VC-L2.

^c Total organic carbon determined by Walkley and Black method.

Table 4

Efficiency of the vermicomposting process.

Process parameters (%)	
Waste-to-biomass conversion rate	3.5
Material reduction (TS basis)	45.9
Material reduction (VS basis)	58.4
Material respired (VS basis)	42.4

between the fresh material and the bottom layer of the vermicompost (VC-L2).

3.3. Mass balance

The material reduction calculated using Eq. (4) was 45.9%, while the material reduction on a VS basis was 58.4%. The biomass conversion rate was 3.5% on a TS basis (Table 4).

Of the 90.4 kg TS of manure and food waste and 0.6 kg worms added to the system, 48.9 kg were converted into vermicompost and 3.8 kg into worm biomass (Fig. 3). In total, 3.2 kg worm biomass was generated and 45.4 kg of oxygen was required for the

respiration of 38.3 kg material. In the process, 62.4 kg of carbon dioxide and 21.3 kg of water were released (Fig. 3).

3.4. Microbial parameters

There was no significant difference ($p > 0.05$) in the concentration of *Enterococcus* spp. and TC between the fresh material and the vermicompost, nor was there any difference in the concentration between VC-L1 and VC-L2 (Table 5). *Salmonella* spp. was found in the fresh material, but not in the vermicomposted material or the worms.

4. Discussion

4.1. Material conversion

According to Edwards (1985), a waste-to-biomass conversion rate of 10% is possible. Mitchell (1997) achieved 4.9% biomass conversion when converting cattle manure to biomass using *E. feotida*. In the present low maintenance, unoptimised vermicomposting system, a waste-to-biomass conversion rate of 3.5% was achieved. Many factors have been found to influence the conversion rate. Yadav et al. (2011) found that the initial worm stocking density dictates which of the two products is optimised (i.e. production of vermicompost or biomass). In that study, a high stocking density (3 kg m^{-3}) yielded a higher waste processing rate (increased vermicompost production), while a lower density (0.5 kg m^{-3}) optimised biomass production. Ndegwa et al. (2000) found that a higher feeding rate ($1.25 \text{ kg.feed kg.worm}^{-1} \text{ day}^{-1}$) generated greater biomass production and also increased waste to biomass conversion. However, although the conversion rate was high, the material processing was not as high and a substantial part of the material was found unprocessed at the end of the experiment. For a better vermicomposting process, a lower feeding rate ($0.75 \text{ kg.feed kg.worm}^{-1} \text{ day}^{-1}$) was necessary.

In this low-maintenance vermicomposting system, the parameters were not highly regulated. The exact feeding rate per worm was not determined, as the total number of worms in the unit was not known at all times, but in the end the feeding rate was around ($0.4 \text{ kg.feed kg.worm}^{-1} \text{ day}^{-1}$). The unit was mainly fed three-day-old cow manure, but also food waste. It was observed that if more waste than the worms consumed was added to the unit, the temperature increased above body temperature, likely due to microbial degradation. In response to the increase in temperature, the worms moved to the edges and top levels, leaving unprocessed material in the centre. This effect was aggravated with an increased percentage of food waste in the feed mix, as it contains more energy. After the first worm harvest (day 63), the feeding rate was better adjusted to the amount consumed by the worms and no build-up of unprocessed material was seen during the remainder of the experiment. At the first worm harvesting, the majority of the worms were large (denoted 'adult worms' in this study), while at the final worm harvesting (day 172), the majority of the harvest-

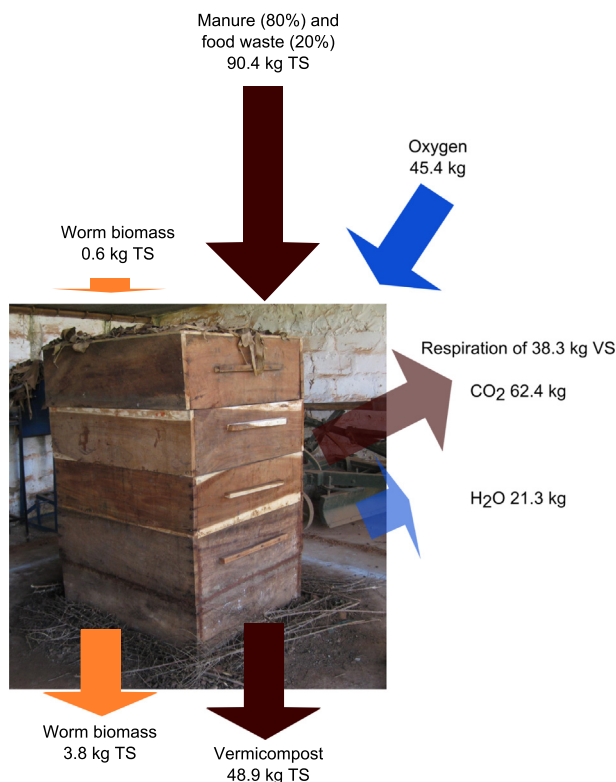


Fig. 3. Mass balance of material in the vermicomposting system on a TS basis; the arrows for worm biomass are amplified ten times.

Table 5

Microbial parameters of the fresh material, the top (VC-L1) and bottom (VC-L2) levels of the vermicompost treatment unit and the worms, mean \pm SD.

	<i>Enterococcus</i> spp. (CFU g ⁻¹)	<i>Salmonella</i> spp. (CFU g ⁻¹)	TC (CFU g ⁻¹)
Fresh	$7.75 \times 10^3 \pm 1.66 \times 10^3$	158 ± 223	$1.37 \times 10^5 \pm 1.25 \times 10^5$
VC-L1	$7.67 \times 10^3 \pm 3.43 \times 10^3$	–*	$3.87 \times 10^5 \pm 1.76 \times 10^5$
VC-L2	$1.13 \times 10^4 \pm 6.51 \times 10^3$	–*	$1.14 \times 10^5 \pm 9.83 \times 10^4$
Worms	$3.09 \times 10^3 \pm 1.98 \times 10^3$	–*	$2.79 \times 10^5 \pm 2.76 \times 10^4$

* Below the detection limit of 10 CFU g⁻¹.

ed worms were smaller (denoted ‘juvenile worms’ in this study). This is likely because of the excess feed available between weeks 5 and 10 (Table 1) allowing for the growth of larger worms. Lower worm densities has been found to yield not only higher biomass production, but also greater mass of the individual worms (Yadav et al., 2011). Along the same line, Vorsters et al. (1997) found that the average individual worm mass decreased with increased worm density. With more frequent harvesting, the worm density could be kept lower and a higher conversion rate could be expected.

The degradation of material was high and the vermicomposted material was visually observed to be porous and homogeneous. It was further noted that it did not smell. The percentage concentration of nutrients decreased as they were incorporated into worm biomass. The concentration of P was rather low, probably because the cows were fed banana leaves, which are low in P (Mohapatra et al., 2010; Katongole et al., 2008).

4.2. Hygiene quality of vermicompost

Many previous studies report the effectiveness of vermicomposting in reducing pathogenic microorganisms (Eastman et al., 2001; Contreras-Ramos et al., 2005; Kumar and Shweta, 2011). However, here the faecal indicator bacteria *E. faecalis* and TC were found in the same concentrations in the processed material and worms as in the inflow material, despite the fact that the material had been well degraded. On the other hand, *Salmonella* spp., present in the inflow material, was neither found in the vermicomposted material nor in the worms. In studies reporting good pathogen reductions, batch systems with retention times between 60 days and six months were used. In a vertical continuous feeding system, such as that used here, it is likely that pathogens are spread through leaching from the top levels down to the more processed levels (Aira et al., 2011). Monroy et al. (2009) demonstrated a high reduction in TC on applying low dosage of pig slurry, but not when applying a large dose. The high volume and constant feeding of this system could have contributed to the low reduction. Leaching from the fresh material to the lower levels, along with the movement of worms, could have transported microorganisms around the unit. Furthermore, the fact that TC, rather than TTC, were determined in this study could be a contributing factor to the high concentrations found. Within the group TTC, around 80% are estimated to be *Escherichia coli*. When incubated at lower temperatures, coliforms originating from other than faecal sources are likely to be included. The TC are thus not as good an indicator of faecal bacteria as TTC. A noteworthy finding was that no *Salmonella* spp. were found in the material in the unit, although fresh material had been added to the system one day prior to sampling, demonstrating the robustness of the vermicomposting system for inactivation of certain bacteria in the *Enterobacteriaceae* family.

4.3. Worms as feed

Earthworms are high in protein, in this study it was found that the worms were 46.3% raw protein (Table 3). Dedekke et al. (2010)

compared the concentrations of essential amino acids of fish meal and worm meal of among others *E. eugeniae*, and found that worm meal and fish meal contained similar concentrations of lysine and methionine while the worm meal was higher in all other essential amino acids but threonine. The concentration of the non-essential amino acid cystine in worm meal is also comparable to that found in fish meal (Kroeckel et al., 2012). The sulphur containing amino acids methionine and cystine are of particular importance for poultry (Sundrum et al., 2005). Worm meal protein is thus comparable to fish meal as protein source in animal feed in general and as poultry feed in particular.

The risk of using worms as animal feed without treatment has to be considered and kept as low as possible, especially when there is a risk of zoonotic disease transmission (transmission of disease between different species of animals and humans). For example, cattle and poultry are both infected by salmonella. As demonstrated in the present study as well as previous studies (Contreras-Ramos et al., 2005; Kumar and Shweta, 2011), salmonella is inactivated during vermicomposting. The risk of spreading salmonella from cattle to poultry in this case should thus be considered low. For a more closed-loop system, or when a risk of zoonotic disease transmission exist, it is advisable to treat the worms (drying, boiling) in order to lower the risks. However, in a large-scale feed production system based on worms, post-processing occur as an natural step, as the feed needs to be preserved and rendered storable, but also mixed with other feedstuffs in order to produce an optimised feed mixture.

4.4. From a urban small-holder farmer's perspective

In order to evaluate the potential of the vermicomposting treatment for urban small-holder farmers, the profit that could be generated in the system described in this study – with the manure of one cow – was estimated (Table 6). The average manure generated per day for different sized animals (Subcommittee, 1993) were used as reference values. The amount of manure generated from one cow can, however, vary for more reasons than the size of the cow, such as among other things the cow breed and the type and amount of feed consumed. The manure collection strategy will also impact the available amount (Paul et al., 2009).

The investment cost for construction of the required area of units included local cost for materials and labour. The unit was expected to have a five year lifetime. The return on investment (ROI) was calculated on a five year net present value (NPV) basis (Eqs. (7) and (8)). The price of the generated worm biomass used was based on the value of fish meal on the Ugandan market. Presently this is a conservative value as the current price of worm biomass is considerably higher due to the lack of alternatives. However, it is likely that this price will decrease when worm meal become more available on the Ugandan market.

For a 450 kg animal the ROI over a five year period was 280%, while it was close to 170% for a 220 kg cow. The potential economic gain using the vermicomposting treatment system could be a considerable contribution to the income of the urban small-

Table 6

The economic potential of vermicomposting manure for a small-holder farmer with one cow of either 450 kg or 220 kg.

	Treatment potential	
	450 kg cow	220 kg cow
Daily treatment capacity 1 × 1 m unit (kg wet)	7	7
Manure generated per day (kg TS) ^a	3	1.5
Required number of 1 × 1 m units	2.3	1.2
Total investment cost (Uganda market, USD) ^b	240	200
Total manure generated yearly (kg TS)	1100	560
Total vermicompost produced in a year (kg TS)	590	300
Total worm biomass produced in a year (kg TS)	40	20
Total raw protein produced in a year (kg TS) ^c	18	9
Equivalent to amount fish meal (kg TS) ^d	29	15
Value of yearly generated raw protein (World market, USD) ^e	52	27
Value of yearly generated raw protein (Uganda market, USD) ^f	29	15
Value of yearly generated vermicompost (Uganda market, USD) ^g	170	90
Total yearly profit (Uganda market, USD)	200	100
Total life time of vermicomposting system (years)	5	5
Five year return on investment (%) ^h	280	170

^a From Subcommittee (1993).

^b Include Ugandan market price for required amount for sand, aggregates, material for base and unit and labour for construction of base and unit (20% of material cost for base and unit, respectively).

^c N (Table 3) × 6.25 = 46.3% of TS.

^d Assuming fish meal to have a TS of 72.5% (St-Hilaire et al., 2007).

^e Valued USD 1820 per tonnes (Index Mundi, 2014a).

^f Valued USD 1 per kg.

^g Valued USD 4 per 50 kg bag.

^h Eqs. (7) and (8): based on interest rate 21.85% (Bank of Uganda, 2014) and yearly inflation of 7.21% using the averaged value for years 1998–2014 (Trading Economics, 2014).

holder farmer: in the slum dwelling of Makindye Division in Kampala it was found that almost 40% lived on less than USD 1 per month, while around 25% had an income between USD 40 and USD 100 per month (Kirabira and Nagaddya, 2012).

The small-holder farmer can favour the production of either worm biomass or vermicompost in the system, depending on what appears more attractive at the time.

4.5. Using vermicomposting as urban manure management strategy

Vermicomposting is a viable option for treatment of manure from urban small-holder animal farms from a technical point of view, as material reduction is greatly facilitating on a relatively small area. However, as the hygienic quality of the vermicompost was found to be low, the use of vermicompost as fertiliser could contribute to spreading of diseases. Allowing for a post-stabilisation step, in which no fresh material is added, could improve the hygiene quality of the vermicompost considerably (Lalander et al., 2013). However, by removing animal manure from the streets and containing it, the risk of disease transmission from the manure is already significantly lowered. Additional management strategies, such as crop selection and spreading techniques, can reduce the risk involved with using the vermicompost as fertiliser (WHO, 2006). If the crop to be fertilised is consumed raw or grows close to the ground, it is advisable to post-treat the vermicompost. A possible post-treatment is ammonia sanitisation. Nordin et al. (2009) demonstrated a 99% inactivation of the eggs of the parasitic intestinal worm *Ascaris suum* when treating faeces with 1% urea (wt/wt) for one month at 24 °C. One month treatment with 1% urea concentration at Kampala ambient temperature would thus render the vermicompost hygienically safe. The annual cost of this treatment would be USD 6.8 in the case of an 450 kg

cow and USD 2.6 in the case of an 220 kg cow; estimated using a urea cost of USD 0.32 kg⁻¹ (Index Mundi, 2014b). The added urea would not only sanitise the vermicompost, but also increase its fertiliser value (Vinnerås, 2007).

The risk of zoonotic diseases transmission when using the worms as feed can be kept at a minimum using management strategies described in Section 4.3. As mentioned, the risk is considerably lowered as the zoonotic pathogen *Salmonella* spp. is inactivated in the treatment.

5. Conclusions

A simple field vermicompost treatment unit was found to operate well even with low maintenance. The unoptimised system proved highly efficient in transforming cattle manure and food waste into odourless, porous and homogenised vermicompost, demonstrating a 45.9% material reduction on a TS basis. The waste-to-biomass conversion rate was estimated to be 3.5% on a TS basis, which is comparable to that found in other, more regulated systems. Increasing the maintenance level slightly, with more frequent worm harvesting, could increase the conversion rate further. The hygiene quality of the vermicompost was low but could be improved by introducing a post-stabilisation step in which no fresh waste is added. Alternatively, ammonia treatment using urea could be introduced as a rapid, low-cost post-sanitisation step.

Vermicomposting has the potential to act as an economic incentive to improve manure management – with an ROI of close to and over 200%, depending on the amount of manure – in urban centres with a high prevalence of animals.

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References

- Aira, M., Gomez-Brandon, M., Gonzalez-Porto, P., Dominguez, J., 2011. Selective reduction of the pathogenic load of cow manure in an industrial-scale continuous-feeding vermireactor. *Biores. Technol.* 102 (20), 9633–9637.
- Albihn, A., Vinnerås, B., 2007. Biosecurity and arable use of manure and biowaste – Treatment alternatives. *Livestock Sci.* 112 (3), 232–239.
- Arancon, N.Q., Edwards, C.A., Atiyeh, R., Metzger, J.D., 2004. Effects of vermicomposts produced from food waste on the growth and yields of greenhouse peppers. *Bioresour. Technol.* 93 (2), 139–144.
- Atiyeh, R.M., Subler, S., Edwards, C.A., Bachman, G., Metzger, J.D., Shuster, W., 2000. Effects of vermicomposts and composts on plant growth in horticultural container media and soil. *Pedobiologia* 44 (5), 579–590.
- Bank of Uganda. 2014. Commercial bank rates. <https://www.bou.or.ug/bou/home.html>.
- Contreras-Ramos, S.M., Escamilla-Silva, E.M., Dendooven, L., 2005. Vermicomposting of biosolids with cow manure and oat straw. *Biol. Fert. Soils* 41 (3), 190–198.
- Dedeke, G.A., Owa, S.O., Olurin, K.B., 2010. Amino acid profile of four earthworms species from Nigeria. *Agric. Biol. J. N. Am.* 1 (2), 97–102.
- Diacono, M., Montemurro, F., 2010. Long-term effects of organic amendments on soil fertility. A review. *Agron. Sustain. Dev.* 30 (2), 401–422.
- Dominguez, J., Edwards, C.A., 2010. *Biology and Ecology of Earthworm Species Used for Vermicomposting*. CRC Press Taylor & Francis Group, Boca Raton, USA, pp. 28–38.
- Dominguez, J., Edwards, C.A., Dominguez, J., 2001. The biology and population dynamics of *Eudrilus eugeniae* (Kinberg) (Oligochaeta) in cattle waste solids. *Pedobiologia* 45 (4), 341–353.
- Eastman, B.R., Kane, P.N., Edwards, C.A., Trytek, L., Gunadi, B., Stermer, A.L., Mobley, J.R., 2001. The effectiveness of vermiculture in human pathogen reduction for USEPA biosolids stabilization. *Compost Sci. Util.* 9 (1), 38–49.

- Edwards, C.A., 1985. Production of feed protein from animal waste by earthworms. *Philos. Trans. R. Soc. B* 310 (1144), 299–307.
- Eleazer, W.E., Odle, W.S., Wang, Y.-S., Barlaz, M.A., 1997. Biodegradability of municipal solid waste components in laboratory-scale landfills. *Environ. Sci. Technol.* 31 (3), 911–917.
- Garg, P., Gupta, A., Satya, S., 2006. Vermicomposting of different types of waste using *Eisenia foetida*: a comparative study. *Bioresour. Technol.* 97 (3), 391–395.
- Henaio, J., Baanante, C., 2006. Agricultural production and soil nutrient mining in Africa – implications for resource conservation and policy development. Tech. rep., An International Center for Soil Fertility and Agricultural Development.
- Hilton, J.W., 1983. Potential of freeze-dried worm meal as a replacement for fish meal in trout diet formulations. *Aquaculture* 32 (3–4), 277–283.
- Hoornweg, D., Bhada-Tata, P., 2012. What a waste – a global review of solid waste management. Tech. rep., World Bank. <<http://documents.worldbank.org/curated/en/2012/03/16537275/waste-global-review-solid-waste-management>>.
- Ibáñez, I.A., Herrera, C.A., Velásquez, L.A., Hebel, P., 1993. Nutritional and toxicological evaluation on rats of earthworm (*Eisenia fetida*) meal as protein source for animal feed. *Anim. Feed Sci. Technol.* 42 (1–2), 165–172.
- Index Mundi. 2014a. Fishmeal monthly price – US dollars per metric ton. <<http://www.indexmundi.com/commodities/?commodity=fish-meal>>.
- Index Mundi. 2014b. Urea monthly price – US dollars per metric ton. <<http://www.indexmundi.com/commodities/?commodity=fish-meal>>.
- Katongole, C.B., Bareeba, F.B., Sabiiti, E.N., Ledin, I., 2008. Nutritional characterization of some tropical urban market crop wastes. *Anim. Feed Sci. Technol.* 142 (3–4), 275–291.
- Katongole, C.B., Nambi-Kasozi, J., Lumu, R., Bareeba, F., Presto, M., Ivarsson, E., Lindberg, J.E., 2012. Strategies for coping with feed scarcity among urban and peri-urban livestock farmers in Kampala, Uganda. *J. Agr. Rural Dev. Trop.* 113 (2), 165–174.
- Kirabira, P., Nagaddya, T., 2012. Report on a situation analysis of the health status of the slum dwelling population along the railway line in Bukasa parish, Makindye division – Kampala. Tech. rep., Department of Research International Health Sciences University.
- Komakech, A.J., Banadda, N.E., Gebresenbet, G., Vinnerås, B., 2014a. Maps of animal urban agriculture in Kampala City. *Agron. Sustain. Dev.* 34 (2), 493–500.
- Komakech, A.J., Banadda, N.E., Kinobe, J.R., Kasisira, L., Sundberg, C., Gebresenbet, G., Vinnerås, B., 2014b. Characterization of municipal waste in Kampala, Uganda. *J. Air Waste Manage.* 64 (3), 340–348.
- Kroeckel, S., Harjes, A.G.E., Roth, I., Katz, H., Wuertz, S., Susenbeth, A., Schulz, C., 2012. When a turbot catches a fly: evaluation of a pre-pupae meal of the black soldier fly (*Hermetia illucens*) as fish meal substitute – growth performance and chitin degradation in juvenile turbot (*Psetta maxima*). *Aquaculture* 364, 345–352.
- Kumar, R., Shweta, 2011. Removal of pathogens during vermi-stabilization. *Environ. Sci. Technol.* 4 (6), 621–629.
- Lalander, C.H., Hill, G.B., Vinnerås, B., 2013. Hygienic quality of faeces treated in urine diverting vermicomposting toilets. *Waste Manage.* 33 (11), 2204–2210.
- Lohri, C.R., Camenzind, E.J., Zurbrugg, C., 2013. Financial sustainability in municipal solid waste management – costs and revenues in Bahir Dar, Ethiopia. *Waste Manage.* 34 (2), 542–552.
- Lumu, R., Katongole, C.B., Nambi-Kasozi, J., Bareeba, F., Presto, M., Ivarsson, E., Lindberg, J.E., 2013. Indigenous knowledge on the nutritional quality of urban and peri-urban livestock feed resources in Kampala, Uganda. *Trop. Anim. Health Prod.* 45 (7), 1571–1578.
- Manfredi, S., Tonini, D., Christensen, T.H., Scharff, H., 2009. Landfilling of waste: accounting of greenhouse gases and global warming contributions. *Waste Manag. Res.* 27 (8), 825–836.
- Memon, M., 2010. Integrated solid waste management based on the 3R approach. *J. Mater. Cycles Waste Manage.* 12 (1), 30–40.
- Meng, L., Ding, W., Cai, Z., 2005. Long-term application of organic manure and nitrogen fertilizer on N₂O emissions, soil quality and crop production in a sandy loam soil. *Soil Biol. Biochem.* 37 (11), 2037–2045.
- Mitchell, A., 1997. Production of *Eisenia fetida* and vermicompost from feed-lot cattle manure. *Soil Biol. Biochem.* 29 (3–4), 763–766.
- Mohapatra, D., Mishra, S., Sutar, N., 2010. Banana and its by-product utilisation: an overview. *J. Sci. Ind. Res.* 69 (5), 323–329.
- Monroy, F., Aira, M., Domínguez, J., 2009. Reduction of total coliform numbers during vermicomposting is caused by short-term direct effects of earthworms on microorganisms and depends on the dose of application of pig slurry. *Sci. Total Environ.* 407 (20), 5411–5416.
- Morris, M., Kelly, V.A., Kopicki, R.J., Byerlee, D., 2007. Fertilizer use in African agriculture – lessons learned and good practice guidelines. Tech. rep., The World Bank.
- Ndegwa, P.M., Thompson, S.A., Das, K.C., 2000. Effects of stocking density and feeding rate on vermicomposting of biosolids. *Bioresour. Technol.* 71 (1), 5–12.
- Nordin, A., Nyberg, K., Vinnerås, B., 2009. Inactivation of ascaris eggs in source-separated urine and feces by ammonia at ambient temperatures. *Appl. Environ. Microbiol.* 75 (3), 662–667.
- OAG. 2010. Value for money audit report on solid waste management in Kampala. Tech. rep., Office of the Auditor General Republic of Uganda.
- Okalebo, J., Gathua, K., Woome, P., 2002. Laboratory methods of soil and plant analysis: a working manual. In: Tropical Soil Biology and Fertility Programme, Second ed., Nairobi, Kenya.
- Paul, S., Onduru, D., Wouters, B., Gachimbi, L., Zake, J., Ebanyat, P., Ergano, K., Abduke, M., van Keulen, H., 2009. Cattle manure management in east africa: Review of manure quality and nutrient losses and scenarios for cattle and manure management. Tech. rep., Wageningen UR Livestock Research.
- Pell, A.N., 1997. Manure and microbes: public and animal health problem? *J. Dairy Sci.* 80 (10), 2673–2681z.
- Pimentel, D., Hepperly, P., Hanson, J., Douds, D., Seidel, R., 2005. Environmental, energetic, and economic comparisons of organic and conventional farming systems. *Bioscience* 55 (7), 573–582.
- R Development Core Team. 2011. R: a language and environment for statistical computing. Tech. rep., Vienna, Austria: R Foundation for Statistical computing. <<http://www.r-project.org>>.
- Reinecke, A.J., Viljoen, S.A., 1988. Reproduction of the african earthworm, *Eudrilus eugeniae* (oligochaeta) – cocoons. *Biol. Fertil. Soils* 7 (1), 23–27.
- St-Hilaire, S., Sheppard, C., Tomberlin, J., Irving, S., Newton, L., McGuire, M., Mosley, E., Hardy, R., Sealey, W., 2007. Fly prepupae as a feedstuff for rainbow trout, *Oncorhynchus mykiss*. *J. World Aquacult. Soc.* 38 (1), 59–67.
- Subcommittee, MPSLW, 1993. Livestock waste facilities handbook. In: Midwest Plan Service. Iowa State University.
- Sundrum, A., Schneider, K., Richter, U., 2005. Possibilities and limitations of protein supply in organic poultry and pig production. Tech. rep., University of Kassel, Wittenhausen.
- Trading Economics. 2014. Uganda inflation rate. <<http://www.tradingeconomics.com/uganda/inflation-cpi>>.
- Viljoen, S.A., Reinecke, A.J., 1992. The temperature requirements of the epigeic earthworm species *Eudrilus eugeniae* (oligochaeta) – a laboratory study. *Soil Biol. Biochem.* 24 (12), 1345–1350.
- Vinnerås, B., 2007. Comparison of composting, storage and urea treatment for sanitising of faecal matter and manure. *Bioresour. Technol.* 98 (17), 3317–3321.
- Vorsters, A., Demey, F., Hardouin, J., 1997. Influence of worm density on the growth of *Eudrilus eugeniae*. *Tropicultura* 15 (2), 89–90.
- WHO. 2006. Guidelines for the safe use of wastewater, excreta and greywater. Tech. rep., World Health Organization.
- World Meteorological Organization. 2014. World weather information service. <<http://worldweather.wmo.int/en/city.html?cityId=1328>>.
- Yadav, K.D., Tare, V., Ahammed, M.M., 2011. Vermicomposting of source-separated human faeces by *Eisenia fetida*: effect of stocking density on feed consumption rate, growth characteristics and vermicompost production. *Waste Manage.* 31 (6), 1162–1168.