Volume 1 Number 1 January 2011
ISSN 2043-9083

Journal of
Water, Sanitation and
Hygiene for
Development

Impact of climate and bulking materials on characteristics of compost from ecological toilets

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ABSTRACT

Urine-diversion dehydration toilets (UDDT) are common throughout the developing world, and the toilet product is widely used as compost. There is no comprehensive research to date that characterizes the compost to determine its quality, extent of pathogen inactivation, and the effects of climate and bulking materials on the compost. Compost was collected from 45 UDDT in Bolivia and analyzed for physical, chemical, and biological parameters. Eighty percent and 56% of samples did not meet acceptable compost guidelines for moisture content and pH, respectively, indicating desiccation was the dominant process in UDDT. Bulking materials significantly impacted compost characteristics in terms of pH, carbon, carbon-to-nitrogen ratio, and carbon stability ($P < 0.05$). Composts with ash exhibited, on average, low carbon concentrations (4.9%) and high pH values (9.7), which can be harmful to plants and composting microorganisms. Composts with sawdust exhibited, on average, high carbon concentrations (40.0%) and carbon-to-nitrogen ratios (31.0). Climate had no significant impact on chemical characteristics, however composts from humid regions had significantly higher moisture contents (34.4%) than those from arid climates (24.8%) ($P < 0.05$). Viable *Ascaris lumbricoides* ova were identified in 31% of samples, including samples with high pH, low moisture contents, and long storage times.

Key words | Ascaris, compost, ecological sanitation, urine-diversion dehydration toilet

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INTRODUCTION

Ecological sanitation is the practice of converting human excreta into compost and liquid fertilizer for beneficial reuse of the carbon and nutrients naturally occurring in feces and urine. It is widely accepted in the scientific community that properly managed human feces and urine can be used as a nutrient-rich organic fertilizer to increase horticultural yield and supplement or eliminate the need for mineral fertilizers (Winblad & Simpson-Hébert 2004). The concept of ecological sanitation is gaining popularity in South America, and in Bolivia there are currently thousands of ecological toilets, and more are built each year.

The most common type of ecological toilet in Bolivia is the double-chamber urine-diversion dehydration toilet (UDDT) built above the ground surface. Urine is diverted and collected separately, and feces are deposited into one chamber at a time. After each defecation event, 1–2 cups of ash, lime and/or carbon-rich bulking materials (e.g. sawdust, rice husks) are added. The bulking materials absorb moisture, detract odors and flies, create a structure in the waste pile that promotes aeration, and adjust the carbon-to-nitrogen ratio in the pile, which can optimize the composting process and product (Jenkins 2005). When one chamber of the UDDT is full, the material is covered and allowed to decompose while users deposit feces in the second chamber. After 6–12 months, or when the second chamber is full, UDDT users are instructed to remove the material and use it for horticultural purposes. During this process of ecological sanitation, it is assumed that two goals are achieved: (1) Pathogens in the feces are inactivated for protection of human health, and (2) The feces and bulking materials are biodegraded and transformed into organic compost.

doi: 10.2166/washdev.2012.059

Pathogen inactivation guidelines for UDDT

Guidelines for the use and maintenance of UDDT are framed in terms of pathogen inactivation. Pasteurization temperatures can be achieved in high-temperature batch composting on a scale of weeks or months; however several studies have determined that high temperatures are not achieved in UDDT (Peasey 2000; Hurtado 2005). Low-temperature composting (composting temperature close to ambient temperature), desiccation, or other aerobic decomposition processes are therefore more likely to occur in UDDT. The most widely circulated guidelines for low-temperature pathogen inactivation in feces suggest storage times of 1.5–2 years in cold climates and >1 year in tropical climates. Storage time can be decreased to 6 months if an alkaline substance such as ash or lime is added as a bulking material and increases the pH to 9 or higher, in addition to temperature >35 °C, and moisture content <25% (Jonsson *et al.* 2004; Schonning & Stenström 2004; WHO 2006).

Field studies have shown a range of times for the elimination of pathogens under the low-temperature decomposition conditions found in UDDT. Nguyen *et al.* (1999) measured pathogen inactivation in UDDT in six months. More recent studies have demonstrated that fecal pathogen indicators, such as the parasite *Ascaris lumbricoides*, continue to live in properly used UDDT after 6 months and up to 2 years (O'Lorcain & Holland 2000; Austin 2001; Corrales *et al.* 2006). Therefore, it is reasoned that proper conditions for pathogen inactivation via pH, moisture content, or temperature are not consistently achieved in UDDT.

Physical, chemical, and biological guidelines for compost

In Bolivia and globally, individuals and community groups use the decomposed UDDT product as compost, and businesses exist to sell the compost and plants grown from the compost. As such, the physical, chemical, and biological characteristics of the UDDT product must adhere to the same guidelines that exist for any organic compost that is used as fertilizer. Acceptable compost guidelines for moisture content, pH, total organic carbon (C), total nitrogen (N), carbon-to-nitrogen ratio (C/N), C stability, nitrogen-phosphorus-potassium ratio (N-P-K), and *A. lumbricoides* ova, as reported in literature, are presented in Table 1. These ranges serve as reference for the results presented in this study. Reported values of pH, C, N, C/N, P, and K for the raw materials that compose ecological toilet compost, including feces and common bulking materials, are presented in Table 2.

There have been no large-scale studies to date that comprehensively characterize the product from UDDT to determine the quality of the product as compost, the dominant decomposition processes that occur in the chambers, the extent of pathogen inactivation, and the impacts of climate and bulking materials on compost characteristics. The following research is a comprehensive baseline study of compost from properly used and maintained UDDT. The goal of this study is to suggest improvements for UDDT design and use to make better, safer compost and increase the success rate of UDDT projects in Bolivia and worldwide.

METHODS

The UDDT product will be referred to as compost through the remainder of this article regardless of its composition because it is commonly referred to and used as compost in the field of ecological sanitation. Compost samples were collected from 45 UDDT in Bolivia from March 2010 to February 2011: 23 samples from the tropical, humid lowlands in the department of Santa Cruz and 22 samples from the temperate, arid highlands in the departments of La Paz and Chuquisaca. Samples were collected from UDDT chambers that had been covered and unused for 6–24 months. Access to communities and UDDT was provided by the organizations that implemented the sanitation projects: Water For People and the *Instituto de Capacitación para el Desarrollo* (INCADE) in Santa Cruz, Plan International in La Paz, and UNICEF in Chuquisaca.

Compost collection

At each UDDT, the access door to the chamber was opened and 20–30 L of compost was removed and placed onto a

Table 1 | Acceptable compost guidelines for selected physical, chemical, and biological parameters as reported in literature

Parameter	Unit	Acceptable range	Comment
Moisture content	% (wet wt)	40–60[a,b]	$<40\%$ limits microbial processes; $<12\%$ stops microbial processes; $>60\%$ creates anaerobic conditions.[h]
pH	–	5–8.5[b,c]	Soil pH is usually close to neutral. Addition of lime or ash raises compost pH to ≥ 10, which can harm soil, plants, and composting microorganisms.
C[i]	%	10–30[b,c]	When C is disproportionately high, soil microorganisms metabolize N and C to produce biomass, rendering N unavailable to plants; if N is too high, it can be lost via volatilization or leaching. C-rich bulking materials are added to increase C/N.
N	%	0.5–2.5[a]	
C/N	–	10–30[b,d]	
C Mineralization	mg CO_2-C/ g $C_{compost}$*d	0–2[e]	Incompletely biodegraded compost contains unstable organic C. When soil microorganisms degrade unstable C, the process depletes N that could otherwise be used for plant growth.
Solvita®	–	7–8[f]	
N-P-K	–	N/A	There is no one ideal N-P-K ratio; general fertilizers are often 1-1-1 (N-P_{P2O5}-K_{K2O}).
Ascaris lumbricoides	Viable eggs/ g dry soil	<1[g]	*A. lumbricoides* ova have been shown to have the longest survival time of most indicator pathogens and are used to predict pathogen inactivation in feces.[h]

[a] Travis *et al*. (2003), [b] Bary *et al*. (2002), [c] CalRecycle, [d] Jenkins (2005), [e] Hutchinson & Griffin (2008), [f] Woods End Laboratories Inc. (2009), [g] World Health Organization (2006), [h] Schonning & Stenström (2004), [i] When necessary, C was calculated from Organic Matter values, assuming 55% C content.

Table 2 | Literature values for pH and chemical composition of the raw materials present in urine-diversion dehydration toilets (UDDT), including human feces and bulking materials

UDDT materials	pH	C (%)	N (%)	C/N	P (%)	K (%)
Human feces[a,b]	7–7.5	40–55	5–7	5–10	3–5.4	1.0–2.5
Wood ash[i,c,d]	9–13.5	3–5	0.02–0.77	25/1	0.1–3	0.1–13
Lime[a,c,e]	9.9–10.35	N/A	0.01	N/A	0.06	0.13
Sawdust[a,e,f]	4.5–7.8	56	0.11	511	0.01	0.0–0.5
Rice husks[a,e,g,h]	6.3, 10.6	36–41	0.2–0.3	121–205	0.05–0.20	0.23–1.08

[a] Jenkins (2005), [b] Tietz (1995), [c] Risse & Harris (2008), [d] Lerner (2000), [e] Kaiser (2006), [f] Ciecko *et al*. (2005), [g] Youri (2004), [h] Wang *et al*. (2005), [i] C, N, and C/N values all from different sources. There can be large variations depending on wood type and burning temperature.

plastic sheet using sterilized equipment. The compost was subsequently mixed using a garden trowel and a representative 2 L was collected in plastic containers. Care was taken to exclude large pieces of notebook and toilet paper, cloth, and synthetic materials. Samples were immediately placed in coolers with ice and analyzed within 24 h. During sampling, surveys were completed with owners of each UDDT to gather pertinent information, including age of the collected compost and type of bulking material used.

Compost analysis

A portion of each sample was dried at 100 °C for 24 h to determine moisture content (wet weight). Another portion was air dried until the change in weight over a 24 h period was less than 1%. Air dried samples were used for analysis of the following parameters using standard methods: pH, C (Walkley-Black method), total Kjeldahl nitrogen, P (Olsen method), and available K (flame atomic emission spectrometry) (Carter 1993). The pH was measured in a 3:1 water:compost slurry that was agitated for 30 min using a Thermo Scientific Orion electrode (9165BNWP) and meter (230A).

Field moist portions of each sample were used for two C stability analyses. Carbon mineralization was measured using a procedure adapted from Carter (1993), and a Solvita® Compost test kit was also used. Both analyses measure the quantity of CO_2 produced during the bacterial decomposition of unstable organic material. Field moist compost was also used for analysis of the viability of *A. lumbricoides* ova, using methodology modified from Bowman *et al.* (2003).

Data analysis

During sample collection, several bulking materials were observed, including sawdust, rice husks, ash, and lime. As the chemical composition of human feces is fairly consistent (Gotaas 1956), it was hypothesized that chemical variation in UDDT compost was largely dependent on the type(s) of bulking material present in the compost. Under this hypothesis, samples were classified by bulking material: alkaline materials including ash and/or lime (A,L); ash and/or lime mixed with a C-rich organic material including rice husks and/or sawdust (A,L + OM); and organic material. During data analysis, statistical significance was determined using *p* values, which were calculated using a two-tailed two-sample unequal variance student's *t*-test.

RESULTS AND DISCUSSION

Averages and standard deviations for all measured parameters in the compost samples are included in Table 3. Typically, samples with a mix of alkaline and C-rich bulking materials (A,L + OM) displayed a range of results between OM and A,L samples. Statistical interpretation of mixed samples is misleading, however, as families use different proportions of bulking materials in their toilets. For this reason, A,L + OM data are included in Table 3, but the statistical analysis is provided for pure OM and pure A,L samples.

Table 3 | Averages and standard deviations of physical and chemical parameters of 45 compost samples taken from urine-diversion dehydration toilets, grouped by bulking material

Bulking material[a]	Moisture content % wet wt	pH	C %	N %	C/N	C Mineralization mg CO_2-C/g $C_{compost}$*d	Solvita	P %	K %
A,L (*n* = 23)	25.7 ± 9.6[b]	9.7 ± 0.9	4.9 ± 3.5	0.83 ± 0.58	7.4 ± 6.3	18.2 ± 14.0	6 ± 2	0.30 ± 0.15	3.62 ± 2.64
A,L + OM (*n* = 16)	33.1 ± 12.9	7.8 ± 1.4	18.5 ± 11.2	1.10 ± 0.70	19.0 ± 10.8	4.8 ± 3.0	6 ± 1	0.51 ± 0.24	2.28 ± 1.21
OM (*n* = 6)	36.0 ± 14.1	6.9 ± 0.5	40.0 ± 10.6	1.84 ± 1.01	31.0 ± 22.0	2.3 ± 0.7	5 ± 1	0.36 ± 0.15	1.40 ± 0.60
P value (A,L to OM)	>0.05	<0.05	<0.05	>0.05	<0.05	<0.05	>0.05	>0.05	>0.05

[a] A,L = ash, lime, OM = C-rich organic material.

[b] The two anaerobic samples were not included in the average, therefore *n* = 21.

Moisture content and pH

Of the 45 compost samples, only 20% met guidelines for moisture content. The remaining samples had moisture content values less than 40%, except two anaerobic samples (>60%) taken from improperly managed UDDT. As the only moisture added to UDDT comes from raw feces, which have moisture contents of 66–83%, the addition of relatively large quantities of dry bulking materials lowered the moisture content to below levels that support composting microorganisms (Hurtado 2005). Hence, the dominant process in the majority of UDDT was most likely desiccation. The average moisture content of samples from Santa Cruz was 34.4% ± 12.7, which was significantly different to samples taken from La Paz and Chuquisaca, which had an average moisture content of 24.8% ± 9.1 ($P < 0.05$). This result suggests that the humidity or aridity of the surrounding environment has an impact on conditions within the UDDT chamber, however both average moisture contents were below the 40% threshold for composting bacteria. The type of bulking material present in the compost had no significant impact on moisture content.

The pH values for all OM samples were within the acceptable guideline for compost. Only 17% of A,L samples and 63% of A,L + OM samples had pH values within the range, most likely due to the alkaline nature of ash and lime. Only 16% of all samples were within acceptable ranges for both moisture content and pH (Figure 1(a)).

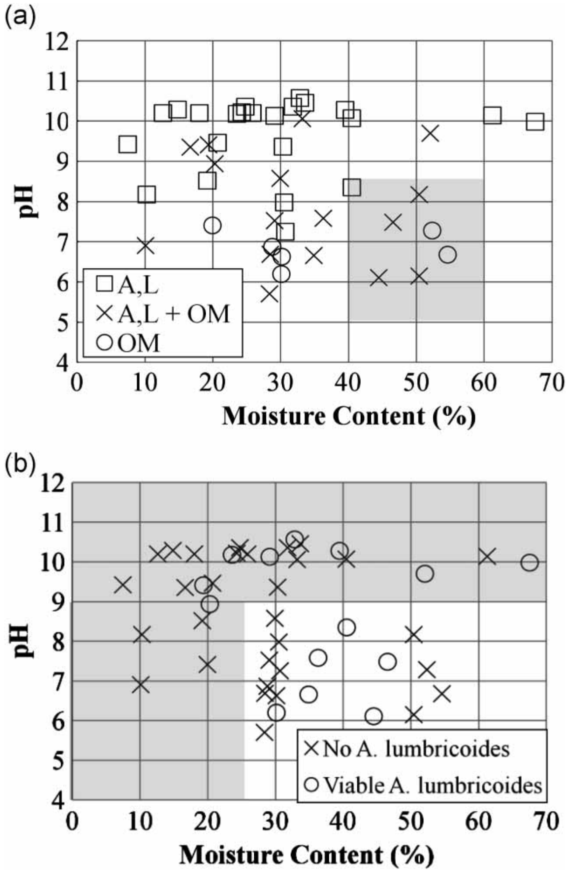

Figure 1 | Moisture content and pH values for 45 compost samples collected from urine-diversion dehydration toilets. (a) Samples grouped by bulking material: ash and/or lime (A,L), carbon-rich organic material (OM) including sawdust and rice husks, and a mix (A,L + OM). The shaded area highlights the acceptable ranges provided in Table 1. (b) Samples grouped by presence/absence of viable *Ascaris lumbricoides* ova. The shaded areas highlight the guideline values for pathogen inactivation provided by the World Health Organization (WHO 2006).

Ascaris lumbricoides

Viable *A. lumbricoides* ova were found in 14 of the 45 samples, including three samples that achieved three of the four World Health Organization (WHO) guidelines for pathogen inactivation, including moisture content <25%, pH >9, and age >6 months (WHO 2006) (Figure 1(b)). It is unlikely that these samples achieved the fourth guideline for pathogen inactivation – temperature >35 °C – however, two of the samples were collected in Santa Cruz where the average summer temperature is 30 °C. An additional five samples with viable *A. lumbricoides* ova met the two WHO guidelines for pathogen inactivation of pH >9 and age >6 months. The remaining six samples with viable ova had been composted for 6–12 months. In every sample with viable ova, the concentration of ova was greater than the WHO guidelines for excreta use in agriculture (<1 viable egg/g dry compost). Therefore, it is concluded that values recommended in literature for pH, moisture content, and age cannot alone be relied upon to inactivate *A. lumbricoides* ova in UDDT to an acceptable level for agricultural use. As high temperatures are not produced in UDDT, the fourth parameter needed to achieve pathogen inactivation – a sustained temperature of >35 °C – can only be met in very hot regions where ambient temperatures provide the necessary heat. More extreme recommended conditions to achieve rapid *A. lumbricoides* inactivation, regardless of temperature – moisture content <5% (Feachem *et al.* 1983; Jiménez *et al.* 2006), and pH >12

(Jiménez *et al.* 2001; Méndez *et al.* 2002) – were not observed in any of the 45 samples collected during this study. These extreme conditions would be difficult to consistently achieve in a UDDT chamber and furthermore, if achieved, would produce a poor quality and potentially harmful compost.

Carbon and nitrogen

Carbon concentrations and C/N values were significantly different for A,L and OM samples. Both the average C concentration and average C/N for A,L samples were below the acceptable guideline ranges and 91% of all A,L samples were outside at least one range. By contrast, C and C/N averages were above the acceptable guideline ranges in OM samples, and no sample was within both ranges. Pure ash and lime have very low C concentrations, while pure sawdust and rice husks have high concentrations, which were reflected in the chemical compositions of the composts. Fifty-six percent of A,L + OM samples were within or close to the acceptable ranges for both C and C/N (Figure 2). These results suggest that, if available, a mix of organic material, such as sawdust, with another material that can eliminate odors and insects, such as ash, is a preferred bulking material for UDDT to achieve higher quality compost.

Seventy-eight percent of all samples were within the acceptable range for N. This result is somewhat surprising as urine is often perceived as containing nearly all of the N in excreta, at 15–19% N (dry wt.) (Gotaas 1956). Raw feces contain 5–7% N (dry wt.) and are perceived as deficient in N; however these results demonstrate that feces in UDDT compost are capable of providing sufficient N to meet plant requirements.

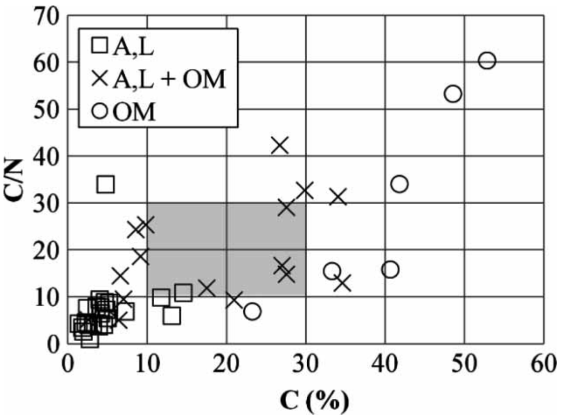

Figure 2 | Carbon and C/N for 45 samples collected from urine-diversion dehydration toilets. Samples are grouped by bulking material: ash and/or lime (A,L), carbon-rich organic material (OM) including sawdust and rice husks, and a mix (A,L + OM). The shaded area highlights the acceptable ranges provided in Table 1.

The two geographical sampling climates had an indirect effect on the chemical characteristics and quality of the compost by nature of the availability of different types of bulking materials. In the tropical lowlands, of the 23 samples collected, 9% contained only A,L, 26% contained only OM, and 65% contained A,L + OM. By contrast, only ash was used as the bulking material in 91% of the 22 samples collected in the arid highlands, 9% contained A,L + OM, and no samples contained OM as the sole bulking material.

Carbon stability

Only four samples had stable C readings for both the C mineralization and Solvita® tests, indicating that decomposition in most of the compost samples had not finished 6–24 months after UDDT chambers were filled and covered (Figure 3(a)). This result can be explained by low moisture content and high pH retarding decomposition. Of the four samples that had stable C, three had rice husks as the bulking material. The rice husks in these samples were visibly identifiable and clearly not composted due to their high concentrations of lignin and silica, which are resistant to decomposition. Therefore, the stable C values most likely indicate that the decomposition of rice husks was slow, not that decomposition had completed.

In general, A,L + OM samples were closer to the acceptable ranges for both stability tests than composts with OM or A,L only, again suggesting that a mix of bulking materials may be appropriate for obtaining high quality compost. Many samples demonstrated poor agreement between the two tests, as low C mineralization readings (indicating stability) did not always correlate with high Solvita® readings (indicating stability). The most likely explanation for the contrasting stability readings is that the Solvita® test is designed for composts containing C/N less than 25, while the C mineralization test is normalized to the quantity of C in the sample and can be used on composts with virtually any C/N. Composts with C concentrations between 10 and 30% generally demonstrated good correlation between the

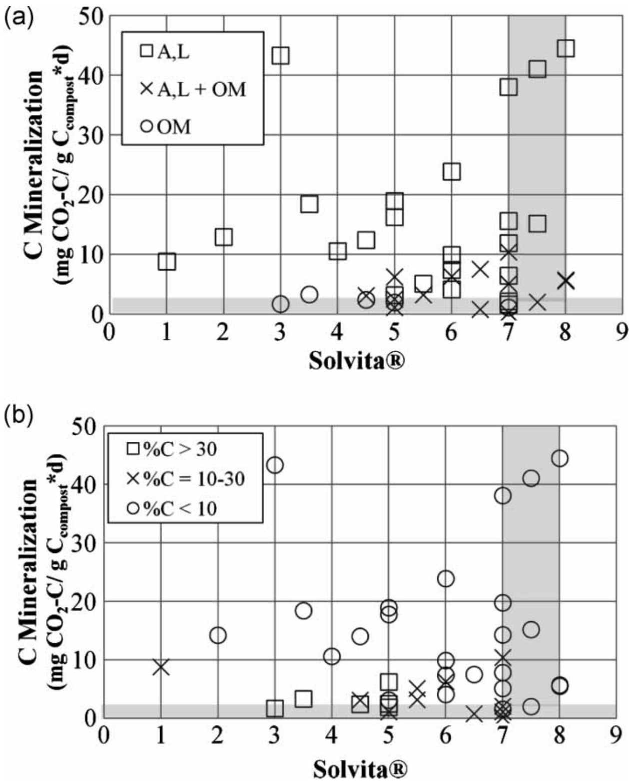

Figure 3 | Carbon mineralization and Solvita® measurements for 45 compost samples collected from urine-diversion dehydration toilets. The shaded area highlights the acceptable guideline ranges provided in Table 1. (a) Samples grouped by bulking material: ash and/or lime (A,L), carbon-rich organic material (OM) including sawdust and rice husks, and a mix (A,L + OM). (b) Samples grouped by C percentage, showing the correlation between the Solvita® and C mineralization analyses.

two stability tests (Figure 3(b)). The C mineralization test was considered more accurate for composts with C concentrations above 30%, but not for samples with C concentrations lower than 10%, because the CO_2 produced was normalized to a very small C concentration, resulting in an apparently very unstable compost relative to the Solvita® result. Conversely, Solvita® generally characterized the OM samples as unstable and A,L samples as stable. These results demonstrate that a combination of stability measurements should be used when analyzing ecological toilet compost.

Implications

These results have important implications for the two goals of ecological sanitation – (1) pathogen inactivation, and (2) compost use as fertilizer. Properly used UDDT did not inactivate all pathogens within 6–12 months, demonstrating that care should be taken when emptying the chamber and handling the compost. The use of ash as a bulking material produced compost with high pH and low C concentrations, making it a poor fertilizer. The use of sawdust produced compost with neutral pH and high C concentrations and C/N, which can deplete soil N if used in large quantities. In general, practices to increase pathogen inactivation, such as raising pH or lowering moisture content will lower compost quality, and practices to increase compost quality will decrease pathogen inactivation. Although both pathogen inactivation and compost use as fertilizer are important components of ecological sanitation, neither one was consistently achieved in UDDT in Bolivia.

CONCLUSIONS

Results indicated that the primary process in UDDT chambers is desiccation, rather than composting. Climate directly affected the moisture content of UDDT compost, and indirectly affected compost quality through the availability of different bulking materials. Bulking material type significantly influenced the composition of the UDDT product. A mix of an easily biodegradable organic material, such as sawdust, with a material that can eliminate odors and insects, such as ash, is recommended as a bulking material. Viable *A. lumbricoides* ova were identified in many samples from properly used UDDT that met most WHO storage criteria for use in agriculture, suggesting that careful use of the compost and hand-washing are essential for minimizing exposure to pathogens. Although this research is exclusive to Bolivia, the implications and conclusions can be extended to other UDDT projects worldwide. Comparable UDDT research in other countries with different climates, cultures, and bulking materials would prove invaluable.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. 0853097. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. The authors acknowledge Dr. William Brinton of Solvita® and Dr. Dwight Bowman of the College of Veterinary Medicine at Cornell University for their support of this research.

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First received 24 August 2011; accepted in revised form 27 February 2012