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Pathogen destruction and solids decomposition in composting latrines: study of fundamental mechanisms and user operation in rural Panama

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ABSTRACT

The relationship between temperature, high pH, desiccation, decomposition, pathogen destruction, and user operation in active double vault urine diverting (DVUD) composting latrines located in the Bocas del Toro region of Panama was assessed. Latrine samples were analyzed for temperature, pH, % moisture, carbon-to-nitrogen (C/N) ratio, and presence of specific pathogens. Surveys and visual inspections were used to verify use and type of dry material desiccant added. Measurements supported findings that compost latrines do not reach temperatures sufficient to destroy all pathogens. pH measurements showed that many latrines were operating within the range for ideal aerobic decomposition, a pH of 7.5–8.5, but only 17% of latrines measured pH 9 or above. Almost 100% of composting latrine users added sawdust and wood ash, to lower moisture level and provide carbon for decomposition. However, the recommended amount of desiccant added was insufficient to reduce moisture to the suggested 25% for pathogen destruction and C/N ratios remained in the range of raw human faeces. Importantly, pathogens, mainly helminths, were still present in compost stored for the 6-month contact time. The latrines have conflicting goals of pathogen destruction and aerobic decomposition. Recommendations are made regarding operation of composting latrines and disposal of composted material.

Key words | composting latrine, developing world, eco-sanitation, helminths, pathogens, sanitation

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INTRODUCTION

Basic sanitation is essential to the health and livelihood of people and their environments. Unfortunately, 2.5 billion people still lack adequate sanitation (United Nations 2008) and inadequate sanitation causes diseases and deaths worldwide – about 2 million people die every year from diarrheal diseases (WHO 2008). To meet this challenge, one of the Millennium Development Goals is to improve access to basic sanitation technology, a critical step in reducing global poverty.

In Panama, 90% of the population has access to various sanitation systems; from latrines to septic tanks to larger wastewater systems. Unfortunately, only 25% of the population within the indigenous reservation, Comarca Ngöbe-Buglé, has access to basic sanitation (Autoridad Nacional del Ambiente 2006). Further complicating matters in this region is a high groundwater table and intermittent flooding from high rainfall on the Caribbean side of the Comarca. This makes a sanitation technology like the conventional pit latrine geographically unsuitable. Accordingly, double vault urine diverting (DVUD) latrines, commonly known as 'composting latrines', which are constructed above ground, have been promoted as an acceptable sanitation technology.

The DVUD latrine commonly implemented is a family-sized, double-vault system with urine separation. The latrine

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is suitable for a family of 8–12 and consists of two 0.75 m^3 concrete block chambers that are used alternately. The first chamber is used for a period of at least 6 months at which time it is sealed and the second chamber is put into use. While the beneficiary uses the second chamber, the contents of the first chamber theoretically decompose in an aerobic environment at a high temperature (the composting process), destroying pathogens and producing usable compost that can be applied to vegetable plants and trees.

Each chamber has its own seat that is designed to capture urine and divert it into a soak pit where it filters into the subsurface. Urine can also be routed to a collection container for use as a fertilizer. Every time a user defecates, they are instructed to add a small amount of desiccant to the latrine. Commonly used desiccants are sawdust, wood ash, rice husks, dry leaves, dry grass, sand, lime, or dry dirt. Detailed information on the design and construction of compost latrines is available elsewhere (Mihelcic *et al.* 2009).

It is assumed, that during this composting process, temperatures are sufficiently elevated for an adequate amount of time to destroy pathogens. However, according to previous studies (summarized in Table 1), the majority of composting latrines in developing countries do not reach high enough temperatures for complete pathogen destruction. These studies suggest that desiccation at high pH may be the primary mechanism for pathogen inactivation. This leads to the questions, 'are the composting latrines in Panama operating under similar ambient temperature conditions', and 'is sufficient dry material being added to reduce moisture levels and/or raise the pH high enough to destroy pathogens?' High pH and low moisture, however, hamper aerobic decomposition, and therefore, the fundamental biochemical processes that produce compost itself. These uncertainties of the fundamental process that occur within the composting latrine also conflict with the education latrine users routinely receive; i.e. their latrines will provide them with a pathogen-free, agriculturally beneficial material.

Pathogen destruction in composting latrines is dependent on temperature, pH, moisture, and storage time. However, the conditions required to destroy pathogens are pathogen specific. The main categories of pathogens found in human excrement in composting latrines can be categorized as: bacteria, viruses, protozoa, and helminths. Helminths are of special consideration, especially the eggs of *Ascaris lumbricoides*. This is because *A. lumbricoides* eggs are very persistent and not easily inactivated (Feachem *et al.* 1983). *Ascaris* ova are also considered the appropriate organism for evaluating treatment effectiveness of a sanitation technology that is to protect public health because their thick shells are very resistant to environmental stressors (EPA 2008).

Infection with the geohelminth *A. lumbricoides*, occurs worldwide, especially in the tropics and subtropics, and is one

Table 1 | Summary of selected studies investigating pathogen destruction in composting latrines

Country	Result/conclusion	Reference
China	A higher pH resulted in greater reduction in pathogens.	Stenström 2002
El Salvador	pH is the most important factor for faecal coliform inactivation, and temperature is the strongest predictor for the inactivation of *Ascaris*.	Moe & Izurieta 2003
Guatemala	pH and humidity are important factors in faecal coliform removal, but appear to not affect *Ascaris* egg die-off.	Peasey 2000
Mexico	Temperatures in the latrines generally at ambient (28°C). Desiccation is the primary mechanism for faecal coliform removal.	Redlinger *et al.* 2001
Mexico	The higher the pH, the lower the % viability of *Ascaris* eggs.	Peasey 2000
Panama	Temperatures and pH values not elevated; moisture content too high to support pathogen destruction. Storage appears to be the only form of treatment, so length of time should be increased.	This study
South Africa	Temperatures did not increase as expected. Storage time, pH, and humidity affect pathogen removal.	Austin 2002
Vietnam	Average temperature was 33.9°C, highest 40.1°C. Temperatures are not hot enough for pathogen destruction.	Chien *et al.* 2001

of the most common helminth infections in humans. It is estimated to have infected 1.472 billion individuals (Bradley & Jackson 2004) and can be controlled through proper sanitation and hygiene measures, and through the discontinuation of using raw sewage, wastewater sludge, or night soil for fertilization, as *A. lumbricoides* eggs can persist in the soil (Feachem *et al.* 1983).

Pit and composting latrines are appropriate technologies for protecting environmental water quality and providing a sanitation barrier to pathogens to protect household health. However, in some geographical coastal areas or areas that experience water scarcity, pit and pour-flush latrines may not be appropriate sanitation technologies respectively. In addition, there is a renewed interest in reclaiming beneficial materials from human waste that cannot only benefit local food production but also improve water quality (Guest *et al.* 2009). In terms of protecting household health, there also appears to be some discrepancy between the message provided to beneficiaries regarding composting latrines. That is, does a compost latrine actually provide pathogen-free compost for agricultural use that can be directly applied to the ground surface? Accordingly, the objectives of this research were to: (1) assess the mechanisms for pathogen destruction in composting latrines in rural Panama; (2) determine if aerobic decomposition at high temperature (composting) is occurring in these latrines; and (3) evaluate whether the composting latrines are being correctly operated to support a particular mechanism(s) for pathogen destruction. The objectives of the research were met by field measurements, laboratory analyses, and community surveys that included observations and interviews over a 6-year period beginning in 2002. The discussion is ended with recommendations related to the future design and operation of composting latrines.

METHODS

Detailed results of this study are available in Hurtado (2005), Kaiser (2006), and Mehl (2008). Laboratory analysis was performed by the Autonomous University of Chiriquí (UNACHI) (David, Panama). The study was conducted in six indigenous Ngöbe communities of the Bocas del Toro region of Panama (Figures 1A and 1B). All the communities received composting latrines in 2003–2004.

Description of sample communities

Table 2 indicates that the six study communities are small in size and located either on, or fairly close to, the main paved highway. All the communities are populated by the indigenous Ngöbe people; mainly subsistence farmers who grow bananas, coffee, cocoa beans, tropical fruits and various starchy root vegetables. Water is provided by gravity-flow aqueducts. Pit latrines are often unsuitable due to flooding and a high groundwater table; therefore, families without access to sanitation often defecate in surface waters.

Temperature field measurements

The temperature of 94 latrines was measured between October to December 2004 using a long-stemmed coil compost thermometer. The compost heap inside the chamber in use was measured, along with chambers that had been sealed off after 6-months of use. The temperature of a smaller subset of 50 latrine chambers was re-measured during September to November 2007, both active and sealed, using a standard mercury thermometer. Thermometers were inserted towards the center of the heap and left a few minutes before removing and recording the temperature. The ambient air temperature was also recorded every four hours.

pH field measurements

The pH of 46 latrine chambers that had been sealed for varying lengths of time was measured during the months of September to November 2007. Using a post-digger, a hole was created from the top and towards the center of the heap inside the latrine chamber. A 5-g sample was collected using a rinsed metal spoon and placed into a clean 200-ml metal can. Then 5 ml of water were added, shaken to mix, and left for the solids to settle. The pH of the supernatant was measured with pH paper. The pH of the 5 mL of water added was also recorded.

Use of desiccant/moisture

The use (and type) of desiccant and overall operation of composting latrines was determined by surveys and visual inspections. All researchers served in this area as water/

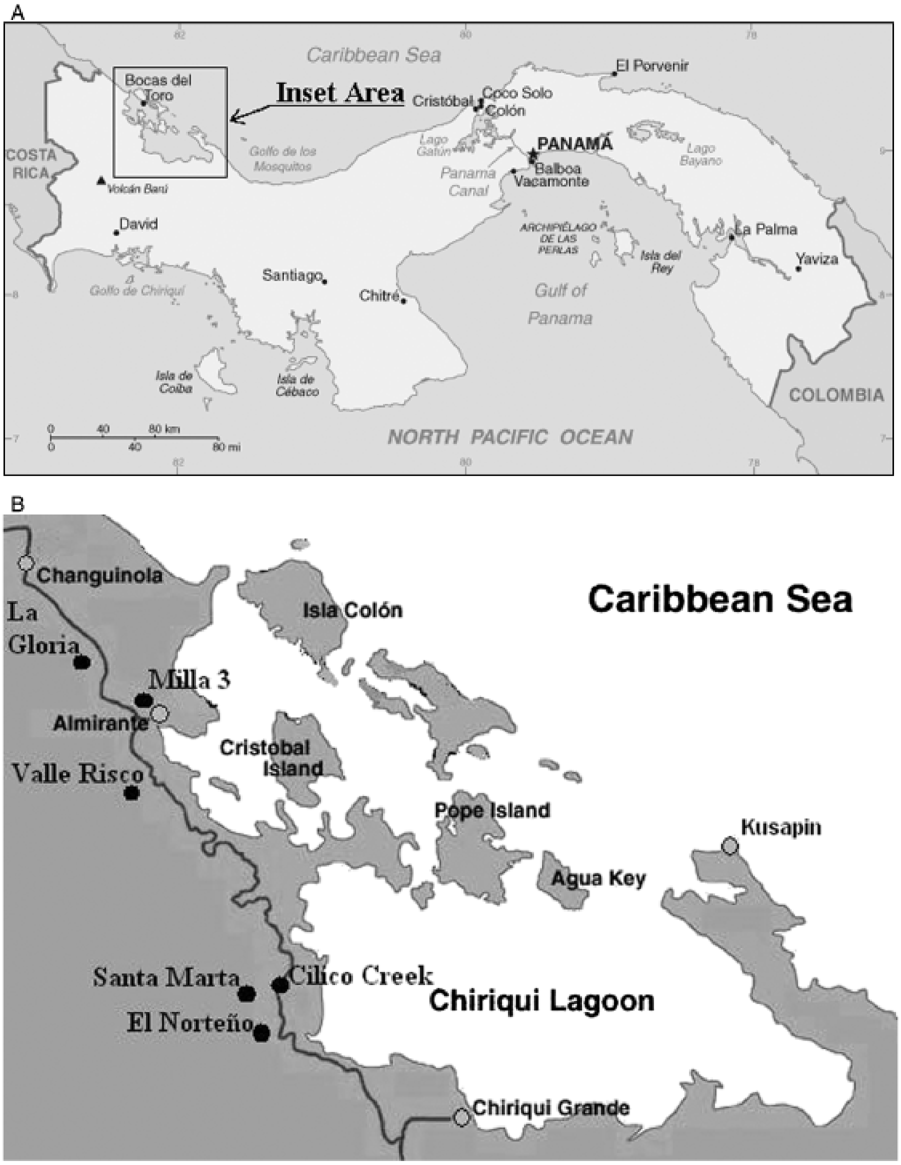

Figure 1 | A. Map of Panama showing inset area detailed below Adapted from *http://en.wikipedia.org/wiki/Image:Pm-map.png* which is based on the Central Intelligence Agency's World Factbook. B. Location of the six communities (indicated by dark circles) included in the survey. Adapted with permission of EnjoyCentralAmerica, *http://www.enjoypanama.com/maps/bocas_del_toro.htm*

sanitation engineers with the Peace Corps through the Master's International graduate school program (*http://cee.eng.usf.edu/peacecorps*). In our first unannounced observations, a designated community leader of the composting latrine project guided the researcher to the latrines in the communities. In our second set of observations, the researcher made an unannounced visit to the communities, accompanied by the closest residing Peace Corps volunteer. At each house the purpose of the visit was first explained and the owners were asked for permission to include the latrine in the study. Our first round of surveying consisted of visually inspecting 76 latrines and interviews of 70 latrine caretakers. The second round of surveying consisted of a visual inspection of a smaller subset of 46 of these latrines, with the exception of asking the latrine owner which side has been sealed and for how long. The inspection criteria are provided in Table 3.

During the inspections, the latrine was first entered and the presence (or absence) of a sack or container of desiccant,

Table 2 | Information on size of communities where sampling took place and distance to highway

Community number	Community name	Approximate population	Total number of houses	Distance from main highway
1	Santa Marta	300	35	30 min walk
2	Cilico Creek	550	34	On highway
3	La Gloria	650	80	20 min walk
4	Milla 3	400	unknown	20 min walk
5	Valle de Risco	1500	126	30 min drive
6	El Norteño	850	80	15 min walk

a scoop to deposit the desiccant, and the type of desiccant present was noted. The contents of the sealed chamber were inspected with the aid of a flashlight, and the presence and type of desiccant inside the compost chamber was noted. The moisture level at the surface of the sealed chamber was visually evaluated using a scale from 1 to 5 using the scoring method provided in Table 4 (5 being the wettest). The odor in the latrine was recorded. In a similar fashion, the overall cleanliness of the latrine was noted. Finally, the physical condition of the latrine was inspected, it was noted whether the seats were properly covered, and any problems were recorded, such as broken urine tubes.

After the inspection, the person who took the most care of the latrine, and who had the best knowledge about the latrine, was identified and interviewed in the local language. In the few cases where the latrine caretaker was a minor, an adult in the house was simultaneously surveyed. The following characteristics were evaluated in the survey (Kaiser 2006): (1) quantity of users, (2) type of desiccant used, (3) amount of desiccant used, (4) method of applying desiccant, (5) latrine odor, (6) use of finished compost, (7) direct training received, and (8) frequency of illness. Many of these characteristics duplicate the same topics as the latrine inspection in an attempt to increase the study's validity (most results are not reported here).

Laboratory analyses

Grab samples were obtained from five composting latrines located in Community Number 5 (Valle de Risco) and transported to the Natural Resources Laboratory at UNACHI. Community 5 was selected because it had the largest number of composting latrines and easy accessibility to the main highway. Factors influencing selection of a particular latrine were the length of time a chamber had been sealed (age of compost), the measured field pH, and the observed moisture level. Table 5 summarizes the character-

Table 3 | Composting latrine inspection criteria

1	Is there a sack/container of desiccant in the latrine? (Y/N)
	If yes, what type of desiccant is it?
2	Is there a scoop present for the desiccant? (Y/N)
3	Is there a presence of desiccant inside the latrine box? (Y/N)
	What type of desiccant is present?
4	Do the contents of the latrine box appear (1 dry . . 5 very wet)?
5	Is the latrine seat covered properly? (Y/N)
6	Is there a bad odor? (1 no odor …. …. .. . 5 bad odor)
7	Is the latrine clean? (1 clean … … … . 5 dirty)
8	Is the latrine in working condition (seats in place, tubes connected, compost doors in place, no major holes etc.)? (Y/N)

Table 4 | Moisture level scale used to make field observations

1	Latrine contents VERY DRY because mostly desiccant material.
2	Latrine contents DRY. Looks like compost, but does not cling together.
3	Latrine contents MOIST. Contents glisten.
4	Latrine contents WET. Contents smear on tools used to take measurements.
5	Latrine contents VERY WET. There is standing water inside latrine chamber.

istics of each of the five latrine grab samples. All of these latrines had been sealed for at least 6 months, with the exception of one latrine, which had been sealed for 4 months. This latrine was included for laboratory analysis because it had the highest recorded field pH, 10.0.

A clean washed metal post-digger was used to dig towards the center of the compost heap. Samples were then randomly collected from four locations – front, left, back, right. This resulted in approximately 150 grams of sample that was sealed in a plastic container. Sample collection required approximately 40 minutes and there was an additional 5 h of waiting and travel time to reach the laboratory. During transport, the samples were kept at ambient temperature or in an air-conditioned environment. The laboratory analyzed samples for carbon-to-nitrogen (C/N) ratio (using the Walkley-Black method for carbon and Kjeldahl method for nitrogen) (Page 1982), pH (using an Orion Research Digital pH meter), % moisture (measuring weight loss after 2 hours of drying at 135°C), and specific pathogenic bacteria, protozoa, and helminths, which are commonly found in human feces (listed in Table 6).

RESULTS AND DISCUSSION

Temperature

Figure 2 provides the temperature measurements obtained from 144 composting latrines surveyed during the six-year study. The average recorded temperature was 29.5°C ($\sigma = 4.3$°C), which is comparable to the average daytime high of 29°C for this region. Only 32% of the latrines surveyed were above the ambient temperature, and only 2% had temperature greater than 40°C. Temperatures greater than 42°C are needed to remove all pathogens within a 6-month storage time. At higher temperatures, >50°C, pathogen destruction proceeds rapidly – one day is sufficient to inactivate many pathogens including *Ascaris* (Cairncross & Feachem 1999).

Thermophilic composting also takes place at these higher temperatures. The term 'composting' refers to aerobic decomposition, and the composting latrine is generally thought to operate under this principle as opposed to anaerobic decomposition. The absence of odors in the majority of the latrines suggests that anaerobic decomposition is not taking place, which corresponds to the latrine design and operation.

The results support the findings of other studies (summarized previously in Table 1) that temperatures of composting latrines do not get high enough to destroy all pathogens. In addition, the temperatures measured do not support the occurrence of thermophilic aerobic composting. Pathogen destruction of bacteria and viruses at ambient temperatures (tropical conditions 20–35°C) could be improved if the contact time were increased to >12 months (Strauss & Blumenthal 1990; Cairncross & Feachem 1999). However, this would require educating latrine users to extend compost

Table 5 | Characteristics of latrines selected for laboratory analysis

Sample	Age of compost (months)	pH measured in the field	Moisture level observed in the field (1 very dry, 5 very wet)
A	10	8.5	4
B	7	7.5	3
C	4	10	3
D	6	6	2
E	6	8	2

Table 6 | Specific pathogens measured in laboratory

Bacteria	Helminths	Protozoa
Total coliforms	*Taenia solium*	*Entamoeba histolytica*
E. coli	*Taenia saginata*	*Giardia lamblia*
Salmonella	*Ascaris lumbricoides*	
Shiguella	*Trichuris trichiura*	
Klebsiella		

storage time and expanding latrine chamber capacity for large families who currently fill a latrine chamber in 6 months.

Especially important is the fate of *A. lumbricoides*. *Ascaris lumbricoides* is used as an indicator for compost quality (EPA 2008). According to the Environmental Protection Agency (2008), the temperature range for incubation of *A. lumbricoides* eggs is between 22 and 32ºC. An unpublished study by Cruz *et al.* (2009) shows that with 21 days of laboratory incubation and temperatures ranging from 28 and 40ºC, *Ascaris suum* showed 73.5–80% viability of the eggs (at pHs of 7 and 9). However, at pH 7 and 9 and a 45ºC incubation, there were no viable eggs in the solution; i.e. all eggs had been inactivated. *Ascaris suum* eggs are more resistant to environmental stressors, so it can be assumed that if *A. suum* becomes inactivated at a certain temperature, then *A. lumbricoides* will be inactivated as well.

pH

The average pH value of 46 samples from sealed chambers was 7.7 (95% CI of 0.3). Thirteen active chambers sampled

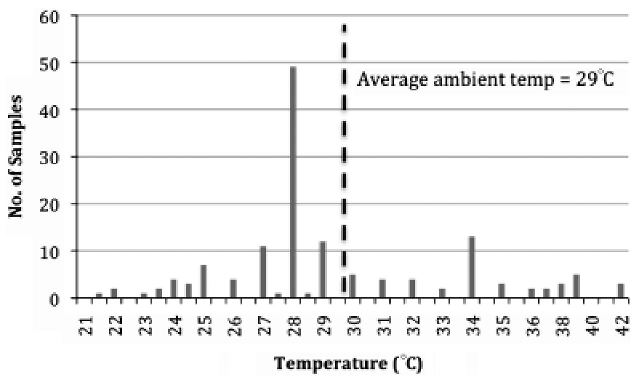

Figure 2 | Temperature measurements taken in 144 composting latrines in the Bocas del Toro region of Panama.

had an average pH of 7.7. This falls within the recommended pH to promote thermophilic composting. Only 17% of the samples obtained from sealed chambers had a pH ≥9 (the pH target for destruction of most pathogenic bacteria and viruses). On the other hand, 65% of samples obtained from sealed latrines had a near neutral or slightly alkaline pH ranging from 6.5 to 8.5.

Figure 3 shows the pH of individual samples categorized according to the type of desiccant observed inside the sealed latrine chamber. The average pH value among the 11 samples using only wood ash was 8.3 ($\sigma = 0.93$); among the 10 samples using both wood ash and sawdust was 7.6 ($\sigma = 0.84$), and among the 25 samples using only sawdust was 7.4 ($\sigma = 1.22$). Of the samples, 36% using wood ash, 12% of the samples using sawdust, and 10% of the samples using wood ash and sawdust had a pH ≥ 9. As expected, more of the samples using wood ash achieved the higher target pH. However, a minority of latrines are achieving the target pH.

Table 7 shows the results of the laboratory analysis for pH for the five grab samples compared with the pH measured in the field. In 3 of 5 cases, the pH measured in the field fell within 0.5 pH units of the laboratory measurements (and a quarter were within 0.68 pH units). One latrine (latrine C in Table 7) exceeded a pH of 9 although our surveys indicated the added dry material was sawdust. Using sawdust alone is not expected to significantly raise the pH of the compost pile. This result may be explained by the location of the grab sample because users will often intermittently add wood ash to the compost pile as a method to control odor and/or flies. This may be because beneficiaries have seasonal access to different desiccants. For example, using wood as a cooking fuel results in a daily supply of wood ash while sawdust is generated from seasonal activities such as logging and home building. Because community access to local desiccants is dependent on income, geography, and climate, this suggests a need for development workers to integrate the specific desiccants employed with the fundamental processes occurring within the latrine.

In terms of pathogen destruction, most pathogens grow at pH of 4–10 (Pelczar & Reid 1972; ESR 2001). *Rotaviruses* have a growth pH range of 3.0–10.0 and *E. coli* have a pH growth range of 4.4–9.0. The optimal pH range for aerobic decomposition of organic matter is 7.5–8.5 (Jenkins 1994). However, a pH of ≥9 is desired for pathogen destruction of most

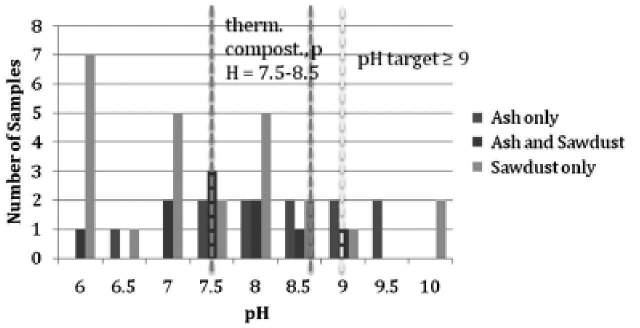

Figure 3 | pH measurements taken inside the sealed chamber of 46 composting latrines in the Bocas del Toro region of Panama and categorized according to the type of additive (wood ash and/or sawdust) observed inside the chamber.

bacteria and viruses (excluding helminth eggs, specifically *A. lumbricoides*). However, pH must be further elevated above 10 to remove more resistant pathogens such as *Vibrio cholerae* and *Rotavirus* spp. In contrast, aerobic decomposition of organic matter is hindered at pH levels greater than 9, presenting a conflict between the breakdown of organic matter and the removal of most pathogens by increased pH. In addition, in the previous section it was mentioned that high pH alone is not sufficient for destruction of helminth eggs and high pH combined with high temperature is needed to effectively inactivate the eggs and destroy pathogenic helminths.

The overall pH of the latrine contents is affected by the pH of the faeces and the added dry material. The pH of human faeces is neutral, ranging from pH 6.6 to 7.0 (Dinoto *et al.* 2006). The two most commonly observed desiccants in our study have literature pH values ranging from 9.4 to11.3 (wood ash) and 4.5 to 7.8 (sawdust) (Mihelcic *et al.* 2009). Adding wood ash to a latrine may thus raise the pH to a suggested value of ≥9 while only adding sawdust will not raise the pH significantly. Moreover, in the unpublished studies carried out by Izurieta *et al.* (2009), sawdust alone decreased the pH to 6, and an equal mixture of wood ash and sawdust increased the pH to an average of 7.9. Therefore, while sawdust is an excellent material to raise the C/N ratio of the compost pile, it is not an appropriate material if the goal is to raise the pH.

Table 7 | pH values measured in the field versus pH values measured in the laboratory, along with the type of desiccant observed in the latrine box

Sample	Observed desiccant	pH measured in field	pH measured in laboratory
D	Sawdust	6.0	6.46
B	Wood ash	7.5	9.45
E	Wood ash	8.0	8.45
A	Wood ash	8.5	9.18
C	Sawdust	10.0	9.48

Moisture and desiccant use

The authors visually observed through unannounced visits that desiccants were being used in 94.7% of latrines during the first survey period and 100% of the latrines during the second survey period. This level of desiccant use was confirmed by surveys of latrine caretakers (e.g. 98.6% of latrine caretakers reported using desiccant additives in the first survey period) (Kaiser 2006). During the second survey period, wood ash and sawdust were observed to be the two most commonly used desiccants: sawdust alone was used more frequently by 60% of users, and an additional 14% of users used a combination of wood ash and sawdust (Mehl 2008). The types of desiccant added was more varied in the results of the interview portion in our first survey period: 95.7% reported using sawdust (20% used solely sawdust), 76.8% wood ash (4.3% used solely wood ash), 7.2% dry grass or leaves, 5.8% dry dirt or sand, 4.3% rice husks, and 4.3% coffee husks.

Moisture levels in the latrines varied. Forty-one per cent of latrine contents were classified as having a moisture level of '3' (appearing moist) followed by 31% of latrines being classified as a '2' (relatively dry due to the desiccant material). For thermophilic (high temperature) aerobic decomposition, the ideal moisture level of the materials composting is suggested to be 40–60% (Cairncross & Feachem 1999). However, to destroy pathogens by means of desiccation, moisture levels should be < 25% (Schönning & Stenström 2004; WHO 2006). Overall, in the second survey, the authors observed 87% of latrines to have moisture conditions supportive for decomposition (moisture levels 2–4), being neither too dry nor too wet.

The moisture contents of the five samples measured by laboratory analysis are provided in Table 8 along with their corresponding 'observed moisture level'. The measured moisture levels are lower than reported for human feces, 66–80% (Jenkins 1994). The moistest samples were obtained from latrines using sawdust as a desiccant. There is also a slight discrepancy between the field observations and the laboratory results. The most probable explanation is that the field observations were based on a top view of the latrine chamber, and the laboratory analyzed samples were collected from the center of the compost heap. The authors have observed this discrepancy for moisture measurements in field studies conducted in El Salvador (data not shown). Moisture moves downward through the compost pile so that the latrine contents towards the bottom of the chamber are generally wetter. Also, latrine caretakers are instructed to add a finishing top layer of desiccant when sealing the chamber, which some caretakers do while others do not.

In terms of optimal conditions to support aerobic composting, two samples fell within the ideal moisture range of 40–60% moisture, and two others were close to this level. However, in terms of pathogen destruction, none of the samples had measured moisture levels below the recommended maximum level of 25%. Accordingly, it appears that the five sampled latrines are not being operated to destroy pathogens by means of desiccation alone. In order to achieve pathogen destruction by desiccation, more dry material needs to be added to the latrine. Interestingly, the samples obtained from latrines that used wood ash rather than sawdust had the lowest moisture levels. Our previous studies in El Salvador showed that wood ash was the best desiccant for decreasing moisture levels, except when compared to lime.

Carbon-to-nitrogen (C/N) ratio

For optimal aerobic decomposition, the C/N ratio of a starting compost pile should be adjusted to 20/1–35/1 (Mihelcic *et al.* 2009). Human faeces have a C/N ratio of only 5–10 which is much lower than the ideal ratio; thus, dry material

Table 8 | Percent moisture measured in laboratory of five samples and the corresponding moisture level observed in the field, along with the type of desiccant observed in the latrine vault

Sample	Observed desiccant	Moisture measured in lab	Observed moisture level
B	Wood ash	29%	3
A	Wood ash	37%	4
E	Wood ash	47%	2
D	Sawdust	50%	2
C	Sawdust	67%	3

that is high in carbon relative to nitrogen should be added if aerobic decomposition is to be achieved. Reported C/N ratios of some of dry materials commonly used in the composting latrines are 200–500 for sawdust and 25 for wood ash (Mihelcic *et al.* 2009). Note that adding only wood ash to raw faeces in a latrine will not provide enough carbon for optimal aerobic decomposition to take place.

Table 9 provides the results of the chemical analysis for C/N ratio for the five grab samples. The samples corresponding to latrines that used sawdust had slightly higher C/N ratios than latrines reported to be using wood ash. The measured C/N ratio for all five samples ranged from 5.4 to 9.2. This is within the expected C/N range of human faeces. While finished compost may have a C/N ratio of 10/1 (Richard & Trautmann 1996), these results, combined with our temperature measurements, suggest that aerobic decomposition is not taking place to a large extent. These low C/N ratio values also suggest that users may need to diversify their preferred desiccant. For example, sawdust is a good choice to increase the amount of carbon available to support the decomposition process while wood ash is a good choice to raise the pH. Non-decomposed compost will not provide immediate benefits to the soil or plants because immature compost can compete for oxygen and nitrogen, have high levels of organic acids, and produce substances toxic to plants (Jenkins 1994). Additionally, the immature compost may contain viable pathogens.

In this location, latrine users are currently advised to add 1–2 handfuls, or approximately 200–500 ml of a desiccant material after defecation. Mehl (2008) performed some calculations to determine how much sawdust would theoretically be needed to achieve a C/N ratio of 30/1, assuming 135 g fecal material are generated per person per day (Jenkins 1994). Those results suggested that 486 ml of sawdust must be added per day per person which means that a family of eight must provide 1.42 m^3 of sawdust every year (Mehl 2008). Obtaining this amount of sawdust may not be practical in all locations around the world, especially those where deforestation has become an increasing problem. Additionally, the sawdust needs to be dry to serve as a desiccant, and many regions of Panama experience prolonged rainy seasons. Even if it were feasible to collect a supply of sawdust once a year during the dry season, finding a place to store it and keep it dry can also be an issue. Several latrine caretakers also

Table 9 | Carbon-to-nitrogen (C/N) ratio measured in laboratory of five compost samples, along with the type of desiccant observed in the latrine box

Sample	Observed desiccant	C/N
B	Wood ash	5.4
A	Wood ash	5.8
E	Wood ash	7.0
C	Sawdust	8.5
D	Sawdust	9.2

reported they did not always have desiccant on hand because it was difficult to find enough to supply the whole family. Furthermore, if thermophilic aerobic decomposition is not occurring in the latrines because the proper environmental conditions are not being met, and instead if pathogen destruction through desiccation is desired, then the use of sawdust is not recommended, as it also does not raise pH high enough to kill pathogens.

Pathogens

The presence of specific pathogens found in the five grab samples is listed in Table 10. Table 11 summarizes the overall results of the sampling in regards to specific pathogens detected and environmental operating conditions of the specific compost pile. Several bacteria, helminths, and protozoa were observed in all five compost samples. For bacteria, total coliforms were observed in all samples, and *Klebsiella* was found in two samples. However, the largest number of total coliforms observed among the samples was only 800 CFU/g, which is much less than the maximum allowable amount of fecal coliforms in EPA Class B compost (2×10^6 CFU/gram) (EPA 1994). For protozoa, an *Entamoeba coli* cyst was observed in one sample. For helminths, the eggs of *Taenia solium* (pork tapeworm) were observed in two sample and the eggs of *Trichuris trichura* (whipworm) in one sample. One sample also had proglottids of *Taenia solium*. *Ascaris lumbricoides* (roundworm) eggs were observed in all five samples.

It is not surprising that many pathogens are still present in the compost after 4–10 months of storage time. As discussed previously, both temperature and pH were not elevated significantly, and moisture levels are too high to support effective pathogen destruction. Six months at ambient temperatures is not sufficient to destroy helminths such as *Taenia* and *Ascaris* eggs. In fact, one day at 50ºC, one month at 45ºC, or one year at 42ºC is needed to destroy *Ascaris* eggs (Cairncross & Feachem 1999). Supporting these findings, studies by Moe & Izurieta (2003) on composting latrines in El Salvador found that temperature is the most reliable predictor for *Ascaris* inactivation, and that pH has minimal effect–*Ascaris* was inactivated after 700 days at pH 9–11.

It follows that those pathogens not observed (*E. coli, Salmonella, Shiguella, Giardia lamblia, Taenia saginata)* were either destroyed by one of the destruction processes or were never present at the onset. Since an initial microbiological analysis was not conducted on the compost samples before storage, it is uncertain whether these pathogens were ever present. Interestingly, one pathogen not found in any sample was *Taenia saginata*, beef tapeworm. Beef is rare in the diet of the Ngöbe people living in the Bocas del Toro region, whereas pork is common (and in the samples, so is the pork tapeworm, *Taenia solium*).

CONCLUSIONS

This study demonstrates that pathogens are not being completely destroyed in all double vault composting latrines used in rural Panama by the fundamental destruction mechanisms of high temperature, desiccation, high pH, and sufficient contact time. A particularly resistant pathogen, *Ascaris lumbricoides* (roundworm) eggs, was also observed in all samples. Only 32% of the latrines recorded above the ambient temperature, and only 2% had a measured temperature greater than the goal of 40°C. Furthermore, addition of dry desiccant material to the compost piles did not achieve pH greater than 9 and/or moisture contents below 25%, known requirements for destruction of most pathogens.

The latrines appear to provide a supportive environment for aerobic decomposition–65% of latrines had near neutral pH values, and 87% of latrines had sufficient moisture levels recommended to promote biological activity. However, the C/N ratio measurements indicate the latrines have C/N ratios similar to raw human faeces, suggesting that insufficient carbon is being added to the latrines to provide optimal conditions for aerobic decomposition. Importantly, during aerobic decomposition, temperatures should rise as thermophilic microorganisms break down organic matter, which

Table 10 | Results of microbiological analysis on the five compost samples (N/O = not observed)

Bacteria					Helminths				Protozoa	
Total coliforms (CFU/100 g)	***E. coli***	***Salmonella***	***Shiguella***	***Klebsiella* (CFU/100 g)**	***Taenia solium***	***Taenia saginata***	***Ascaris lumbricoides***	***Trichuris trichura***	***Entamoebas***	***Giardia lamblia***
8.E+04	N/O	N/O	N/O	N/O	N/O	N/O	infertile egg	infective egg	Entamoeba coli cyst	N/O
7.E+03	N/O	N/O	N/O	N/O	eggs	N/O	infertile egg	N/O	N/O	N/O
3.E+04	N/O	N/O	N/O	4.E+03	adult sections and eggs	N/O	egg	N/O	N/O	N/O
3.E+04	N/O	N/O	N/O	6.E+03	N/O	N/O	fertile egg	N/O	N/O	N/O
7.E+04	N/O	N/O	N/O	N/O	N/O	N/O	infertile egg	N/O	N/O	N/O

subsequently destroys pathogens. The detection of several specific pathogens after the recommended 6-month storage time suggests this recommended time period may be too short, especially when contact time appears to be an important control parameter, especially in the absence of high temperatures, high pH values, and low moisture content.

Latrine users should be educated to operate their latrines to achieve one of two strategies. The first is to add additional dry, high pH, desiccants such as wood ash (or lime) to the latrine to increase the pH above 9 and decrease moisture content below 25%. Alternatively, a wider variety of high carbon dry materials, such as grass, leaves, and straw should be added to increase the C/N ratio and with sufficient turning of the pile, promote the activity of thermophilic aerobic organisms that degrade the organic matter and subsequently raise the temperature of the compost pile above 40°C. Our study demonstrates the conflicting and incompatible fundamental operating conditions communicated to beneficiaries, and mechanisms occurring within the compost pile, for compost latrines located in the developing world. That is, pathogen destruction methods that promote high temperature, high pH, and low moisture are not compatible operating goals. Further research should be conducted on what effect adding a variety of dry materials to the latrine contents has on temperature and decomposition. If the effects were in favor of thermophilic aerobic decomposition, the destruction of pathogens could then be evaluated.

Since composting latrines are designed with a primary goal to prevent human exposure to pathogens, destroying pathogens in the latrine while also preventing re-exposure from pathogens that survive in the finished compost that is reapplied to soil should be considered operating objectives. Our first recommendation is to increase the storage time of the compost from 6-months to a minimum of 1-year. Latrine owners should be educated that the longer they store the compost, the lower the risk of pathogen survival of bacteria and viruses. Unfortunately, this does not hold true for inactivation of helminth eggs such as *A. lumbricoides*, because they are proven to be environmentally persistent, even at long storage times at ambient temperatures, regardless of pH.

A longer storage time may present a problem in some cases as many existing composting latrines have been designed to accommodate a 6-month accumulation of solids and desiccant materials. The composting latrine design can

Table 11 | Summary of environmental characteristics of the five compost samples and the pathogens observed

Sample ID	Age	pH	Moisture	Observed desiccant	Pathogens
A	10 mo.	9.18	37%	Wood ash	Total coliforms, *Ascaris lumbricoides, Trichuris trichura, Entamoeba*
B	7 mo.	9.45	29%	Wood ash	Total coliforms, *Taenia solium, Ascaris lumbricoides*
C	4 mo.	9.48	67%	Sawdust	Total coliforms, *Klebsiella, Taenia solium, Ascaris lumbricoides*
D	6 mo.	6.46	50%	Sawdust	Total coliforms, *Klebsiella, Ascaris lumbricoides*
E	6 mo.	8.45	47%	Wood ash	Total coliforms, *Ascaris lumbricoides*

be easily adjusted in the future by constructing larger volume chambers, though the added cost for materials may be costly to some beneficiaries. Education for latrine users should continue to encourage the use of adding sufficient desiccant, with a clear goal of either achieving increased pH and decreased moisture, or increased C/N ratios with sufficient moisture and aeration of the pile by periodically turning it.

With regard to use of the final composted materials, the authors suggest the following: (1) the aged compost should be collected during the dry season, or if there is no marked dry season, during the less rainy time of the year on a clear day. The aged compost should then be allowed to solar-dry for one week. This is best done by spreading the compost on zinc sheets in a thin layer ($\leq$10 cm) under full sunlight. The likelihood of helminth eggs persisting in the compost, even after being solar-dried, determines the need for further studies to confirm that *A. lumbricoides* eggs are being inactivated when exposed to direct sunlight. (2) In communities where agriculture is not carried out, the solar dried or non-solar-dried compost can be buried under 10 cm of soil that is deep enough to account for local conditions of soil erosion during heavy rains, is 300 m away from surface water and food sources, and where children and animals will not have easy access to it. (3) The composted material should not be placed on agricultural fields with crops that grow on the ground and are eaten raw. The solar-dried compost should only be used if the nutritional benefit of fertilized crops outweighs the risk of possible pathogen contamination by helminths. In order to reduce this risk, it is recommended to bury the solar-dried material 10 cm deep around banana, coconut, or papaya trees, or around crops that grow over the ground and are eaten cooked, such as corn or wheat. However, in order to prevent spread of diarrheal disease, it is recommended to never use the material for vegetables or fruits that grow over, or under, the ground and are eaten raw; e.g. lettuces, carrots, or strawberries.

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