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Survival of Fecal Coliforms in Dry-Composting Toilets

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The dry-composting toilet, which uses neither water nor sewage infrastructure, is a practical solution in areas with inadequate sewage disposal and where water is limited. These systems are becoming increasingly popular and are promoted to sanitize human excreta and to recycle them into fertilizer for nonedible plants, yet there are few data on the safety of this technology. This study analyzed fecal coliform reduction in approximately 90 prefabricated, dry-composting toilets (Sistema Integral de Reciclamiento de Desechos Orgánicos [SIRDOs]) that were installed on the U.S.-Mexico border in Ciudad Juárez, Chihuahua, Mexico. The purpose of this study was to determine fecal coliform reduction over time and the most probable method of this reduction. Biosolid waste samples were collected and analyzed at approximately 3 and 6 months and were classified based on U.S. Environmental Protection Agency standards. Results showed that class A compost (high grade) was present in only 35.8% of SIRDOs after 6 months. The primary mechanism for fecal coliform reduction was found to be desiccation rather than biodegradation. There was a significant correlation (P = 0.008) between classification rating and percent moisture categories of the biosolid samples: drier samples had a greater proportion of class A samples. Solar exposure was critical for maximal class A biosolid end products (P = 0.001). This study only addressed fecal coliforms as an indicator organism, and further research is necessary to determine the safety of composting toilets with respect to other pathogenic microorganisms, some of which are more resistant to desiccation.

Urban and periurban areas in developing countries often lack adequate sanitation services for their rapidly growing populations (11). Lack of the following accounts for this: financial resources, available water and space, and institutional infrastructure. Many cities are experiencing or by the year 2010 will encounter water shortages, which are a major threat to public health (1, 14, 15).

Urban growth taking place in informal settlements is often overlooked by municipal governments, which are unable or unwilling to provide piped water and sewage infrastructure. As a result, many low-income households must rely on pit latrines or cesspools. This solution is often not practical because of space requirements for pits, rocky soil conditions, and well water contamination. Pathogens escaping from poorly constructed pit latrines and septic tanks have been shown to contaminate groundwater and surface waters (12).

One approach to safe and sustainable sanitation is the use of dry sanitation toilets (5). These systems promote recycling of human excreta, which can be returned to the soil as fertilizer after pathogen reduction. Pathogen reduction can occur by either dehydration or biodegradation (10).

Dry sanitation systems require neither water nor sewage infrastructure for their operation (8). They replace the pit latrine and have two advantages: they do not pollute the environment and biosolid waste is sanitized. These systems have the potential to improve public health by reducing illnesses caused by fecal-oral transmission of pathogens.

In 1999, approximately 300 prefabricated, dry-composting toilets (Grupo de Tecnología Alternativa) (Naucalpan, Mexico) were installed on the U.S.-Mexico border in three Ciudad Juárez communities in the state of Chihuahua, Mexico. These units, called Sistema Integral de Reciclamiento de Desechos Orgánicos (SIRDOs), are single-vault, solar composting systems. SIRDOs are self-contained fiberglass and plastic structures that stand apart from a home and usually serve a single family.

This study tested 90 SIRDOs to classify biosolid waste end products as class A or B based on U.S. Environmental Protection Agency (EPA) standards with respect to fecal coliform counts. Fecal coliforms are bacteria meeting these criteria: aerobic and facultative anaerobic, gram-negative, non-spore forming, and rod-shaped (4, 7). In addition, they grow and ferment lactose with the production of gas and acid at 44.5°C, which is the property that permits their enumeration in the multiple-tube technique (6). This study not only measured the reduction of these bacteria but also determined the primary mechanism (biodegradation or dehydration) for reducing fecal coliforms. Both of these goals were important so that user maintenance can be optimized to yield a safer end product and so that user disposal methods can be determined.

MATERIALS AND METHODS

The study area was located on the outskirts of Ciudad Juárez, Chihuahua, Mexico, and included the three colonias of Nueva Galeana, Plutarco Elias Calles, and Felipe Ángeles. These communities lacked municipal sanitation services, and most did not have piped water to their homes. Before the introduction of SIRDOs into the communities, most participants had pit latrines or an indoor flush toilet that emptied into a pit outside the home. Study participants were of low socioeconomic status, with an average yearly income of $3,300.

Dry-composting toilets. A local foundation provided 300 SIRDOs, and lay health promoters coordinated ecological-theatre events where participants learned SIRDO operation and management. Families were assigned a community health promoter who visited them on a regular basis to assist with SIRDO maintenance. Study participants also received an instruction booklet for SIRDO operation and a calendar to remind them of the recommended SIRDO mainte-

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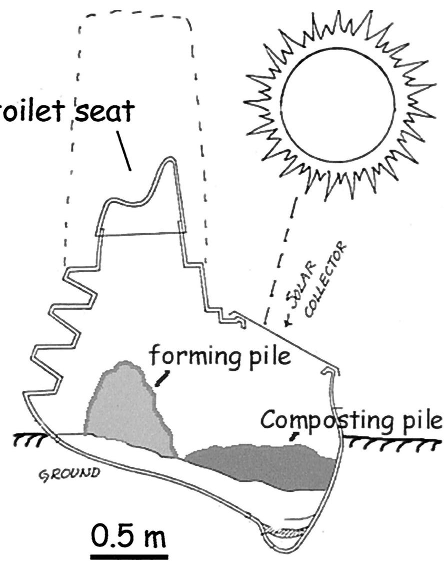

FIG. 1. Diagram of a single-vault SIRDO showing the forming pile, which is pulled down after 3 months to produce the composting pile. The composting pile is located in a secondary processing area where composting continues without the addition of new waste. The solar collector is positioned directly over the composting pile and helps maintain elevated temperatures required for biodegradation or desiccation. Urine is contained in the secondary processing area and is not allowed to contaminate the environment.

nance schedule. Since study participants were new to the concept of dry sanitation and composting, training and support were an integral part of the program.

A cohort design was used to follow a random sample of 90 families using SIRDOs. The quality of biosolids from the SIRDOs was measured at two intervals: 3 and 6 months after installation. Study variables included fecal coliform quantification and moisture content of biosolid waste samples, stirring the compost heap (aeration), solar exposure, temperature of composting material, and user maintenance. For the 3-month sampling, the accumulated pile had just been pulled down into the secondary processing area, which separates it from new waste additions (Fig. 1). This is the beginning of a 3-month period during which the composting pile must be aerated by stirring one or two times per week. The recommended period for composting the heap is 3 months after pulldown (SIRDO instruction manual). After this 3-month period in the secondary processing area, the biosolid waste is removed for disposal. The cycle is repeated by pulling down the forming pile to begin the composting phase. Consequently, the 3-month sample is collected at the time of pulldown, and the 6-month sample is collected just before biosolid removal for disposal.

Sample collection and analyses. Samples were taken from five different sites in the composting heap, combined, and mixed into one homogeneous sample consisting of 100 to 200 g (fresh weight). Samples were transported to the laboratory in an ice chest within 2 hours of collection and were analyzed for fecal coliforms on the same day. After analysis, samples were disinfected or autoclaved.

Five grams of the biosolid waste sample was desiccated in a drying oven for 24 h, after which the sample was immediately weighed and dry weight measurements were calculated as a percentage of wet weight. Fecal coliform concentrations were estimated using the multiple-tube fermentation direct test (A-1 medium [13]) as described previously for the EPA Standard Method 9221 E (2). Eleven grams of the biosolid waste sample was mixed with 99 ml of sterile water and was blended for 40 s in a sterile, stainless-steel Waring blender at low speed. Serial dilutions of the slurry were made, and 10 ml of the 10^{-4}, 10^{-5}, and 10^{-6} dilutions was added to 1 ml of A-1 medium (Hach, Loveland, Colo.). The concentration of the A-1 medium was adjusted to conform to the standard medium described for the EPA Standard Method 9221 E (2). Tube contents were incubated at 37°C for 3 h, small bubbles were removed, and the materials were again incubated at 44.5°C for 21 h before results were recorded. Gas in the inverted Durham tube and turbidity of the medium indicated positive results, and the most probable number (MPN) was estimated by using an MPN table.

Biosolid waste classifications. MPN data was categorized into EPA standards of class A and class B compost. Based on these classifications (16), class A compost contains safe and acceptable levels of pathogens and is a safe soil amendment for food and nonfood plants. It must contain <1,000 MPN fecal coliforms per g. Class B compost is a safe soil amendment for ornamental plants and must contain $<2 \times 10^6$ MPN fecal coliforms per g. In this study, we followed the above EPA recommended values for class A and class B compost with respect to the MPN of fecal coliforms. Those samples with an MPN greater than 2×10^6 fecal coliforms per g did not fit in either class A or B, so they were placed in a separate division, class C. The moisture content of biosolid samples was divided into three groups: <40, 40 to 60, and >60%. These groups were established for this study based on reported moisture content considered optimum for aerobic biodegradation (3, 5, 8).

Statistical analysis. All data were analyzed utilizing Statistical Package for the Social Sciences (SPSS) statistical software, and chi-square tests were employed to determine significant correlations. Logistic regression was used to identify the relationship of environmental and household factors with the quality of biosolid waste while controlling for the effect of other variables. The fit of the model was evaluated using the Hosmer-Lemeshow goodness-of-fit test (9).

RESULTS

Biosolid fecal coliforms. To evaluate the best approach to analyzing biosolid fecal coliforms, we first looked at the relationship between the MPN and moisture levels as one of the continuous variables (Fig. 2). There was a wide distribution of points at all moisture levels with high standard deviations; thus, our ability to detect valid relationships among study variables was limited. Therefore, categorical variables were used to represent fecal coliforms and percent moisture, using biologically relevant groups as defined in Materials and Methods.

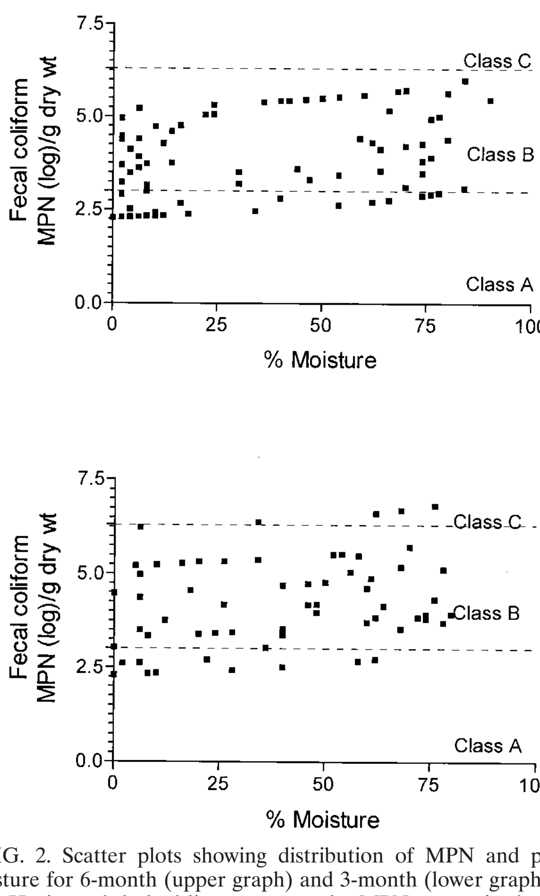

FIG. 2. Scatter plots showing distribution of MPN and percent moisture for 6-month (upper graph) and 3-month (lower graph) samples. Horizontal dashed lines separate the MPN categories based on fecal coliform counts: class A, class B, and class C.

TABLE 1. Biosolid classification at 3 and 6 months

Time (mo)	Classification				
	Class A % (n)	Class B % (n)	Class C[a] % (n)	Indeterminate[b] % (n)	Total (n)
3	19.4 (13)	70.6 (48)	6.0 (4)	3.0 (2)	67
6	35.8 (29)	60.5 (49)	0	3.7 (3)	81

[a] Samples with fecal coliform levels exceeding those of class B (MPN, $>2 \times 10^6$).
[b] Not able to determine class.

Biosolids were measured at 3 and 6 months. For both the 3- and 6-month samples, class B was the most abundant classification at 70.6 and 60.5%, respectively, with the greatest percentage occurring at 3 months (Table 1). On the other hand, class A samples, although not the dominant class, significantly ($P = 0.043$) increased at 6 months (35.8%) from the 3-month period (19.4%). This demonstrated that with respect to fecal coliform reduction, one-third of SIRDOs produced a high-grade end product. Also, by 6 months there were no samples with extremely high fecal coliform counts (class C). Missing data reflected in the totals resulted from inability to collect samples because study participants were not at home.

Moisture content. Moisture content in the compost pile is related to the amount of soak materials that are added after using the facilities. Almost all SIRDO users deposited toilet paper (89%) and sawdust (96%) into the forming pile. As a result, it was difficult to determine the effect of depositing these soak materials in the compost pile with respect to moisture content and compost classification rating. The high content of soak materials in samples indicated that SIRDO users were following required protocol for managing their SIRDO units.

Odor associated with toilets is a primary concern of users. In general, when the moisture content of the heap was low (<40%), unpleasant odors were significantly less noticeable ($P < 0.003$). Smell was a subjective measure and was determined by the sampler at the time that the biosolid waste sample was taken. Results from this study showed that 64.5% of the units did not have a detectable odor.

At the ideal moisture content for aerobic biodegradation (40 to 60%), only four samples met the class A requirements (Table 2). In fact, only 18.0% of all samples fit into the ideal moisture content range for aerobic biodegradation. On the other hand, more than half (54.0%) had a moisture content of <40% and this group also had the highest percentage (73.8%) of class A compost. The relationship between biosolid classification rating at 6 months and moisture content showed that there was a significant correlation ($P = 0.008$) between the classification rating and the percent moisture categories of the biosolid samples. These findings, taken together, indicated that the reduction of fecal coliforms was primarily the result of desiccation and not of aerobic biodegradation.

Since desiccation was the primary method of disinfection, moisture categories were combined to focus on reduced moisture (one group of <40% and another of 40 to 100%). Using these new categories, moisture content was evaluated for 3 versus 6 months, but no significant difference was found, although there was a trend in the direction of lower moisture content at 6 months (data not shown). These results indicated that by 3 months, half of the samples already had reduced moisture content (<40%) and that this did not change significantly during the ensuing 3 months.

There was a small number of class A cases (16.7%) that had a moisture content of >60% (Table 2). These cases were not the result of desiccation and not likely the result of aerobic biodegradation, since high moisture content excludes oxygen. The most probable cause of this reduction in fecal coliform was anaerobic biodegradation. This was confirmed by a significant correlation ($P = 0.003$) for moisture content of >60% and associated unpleasant odors which are produced during anaerobic biodegradation. The increase in class A samples at a moisture content of >60% was not significant, but there was a trend (Fishers exact test, $P = 0.168$) to more class A at 6 months (24.0%) than at 3 months (7.1%).

Composting heap temperature. A characteristic of thermophilic aerobic biodegradation is a rise in temperature almost immediately after pulldown and stirring to aerate the pile. Pile temperatures should rise due to microbiotic aerobic metabolism and may reach 70°C (3). In this study, the temperature of the heap was measured by placing a thermometer in the middle of the heap. In general, temperatures of the compost heaps were usually equal to or similar to the ambient temperature. There was only one case where there was a significant difference between the ambient and pile temperatures (28 and 40°C, respectively), and this pile temperature still did not fall within the optimum range for thermophilic bacteria. Therefore, pile temperature data indicated that composting heaps were not generating heat by aerobic thermophilic microorganisms.

Composting heap aeration. When there are high moisture content and insufficient soak material such as sawdust to increase pore space, oxygen is restricted to the outer surface of the heap. Thus, stirring or turning over the compost heap is important to encourage growth of aerobic biodegradation microbes. To determine if the composting heap had been properly stirred, we employed a subjective estimate by the sample collector as to the condition of the heap. This was based on observations of the presence of spiderwebs, large lumps of fecal material, and in general, a lack of smooth consistency. The condition of the heap was classified into two groups: mixed and not mixed. This variable was a reflection of user maintenance of their SIRDO.

In the 6-month sampling, 37.3% of SIRDOs appeared not to have been mixed, while 62.5% were mixed. The correlation between classification of the biosolids and whether they were stirred was not statistically significant ($P = 0.200$). This result was not surprising, since aerobic biodegradation did not appear to be the primary method for fecal coliform reduction as noted above.

TABLE 2. Relationship[a] of classification ratings and moisture content of 6-month biosolid samples ($n = 139$)

% Moisture content	Classification		
	Class A % (n)	Class B % (n)	Total % (n)
<40	73.8 (31)	45.4 (44)	54.0 (75)
40–60	9.5 (4)	21.6 (21)	18.0 (25)
>60	16.7 (7)	33.0 (32)	28.1 (39)

[a] χ^2 $P = 0.008$.

TABLE 3. Logistic regression analysis for predictors of Class A biosolids

Parameter	P^e	Odds ratio	95% confidence interval
Solar exposure	0.011	10.22	2.2, 47.6
Low moisture[a]	0.057	3.66	1.5, 9.1
Time[b]	0.471	1.20	0.9, 1.6
Aeration[c]	0.771	0.79	0.3, 1.9
Temp[d]	0.984	0.95	0.9, 1.1

[a] Moisture content of <40%.
[b] Six months and 3 months. Three months is the reference.
[c] Compost heap was not stirred.
[d] Difference between ambient temperature and that of compost heap.
[e] Hosmer-Lemeshow goodness of fit $\chi^2 = 3.98$; $P = 0.86$.

Solar exposure. Solar exposure is important for two reasons. First, it heats the composting vault and promotes active biodegradation by thermophilic aerobic microorganisms. Second, it lowers moisture of the pile and prevents flooding due to excessive urine content. Seventy-eight percent of the SIRDO units had solar exposure, which is defined by southern orientation of the passive solar panel on the SIRDO unit and no blockage of the panel to solar irradiation. There was no significant correlation between solar exposure and moisture content, although there was more dehydration with solar exposure (53 versus 47%). This result reflects the earlier finding that by 3 months, half of biosolid samples already had low moisture content. On the other hand, there was a significant correlation between solar exposure and compost classification ratings ($P = 0.001$). Ninety-five percent of the composted samples with class A ratings were from SIRDOs with solar exposure. This illustrates the importance of solar exposure and SIRDO directional orientation to achieve a high-quality end product.

Multivariate analysis. A logistic regression analysis was conducted to estimate the effects of environmental factors and user maintenance on class A biosolids (Table 3). Solar exposure of SIRDOs remained highly correlated to class A production. The odds ratio showed that class A biosolids were 10.2 times likelier to occur with solar exposure. Low moisture was another influential indicator of class A biosolids, with an odds ratio of 3.6. As indicated above and in this model, neither temperature nor aeration of the heap showed a significant correlation with class A biosolids. The variable "time" (3 months and 6 months), although not significant, was in this model to control for any potential differences between the 3- and 6-month samples. The Hosmer Lemeshow test showed a good fit for the model (Hosmer-Lemeshow goodness of fit, $\chi^2 = 3.98$; $P = 0.86$).

DISCUSSION

In this study, we investigated fecal coliforms only as indicator organisms. Other pathogens, especially those forming spores or eggs, may be less affected by biodegradation and desiccation and can survive for much longer times. Thus, the reduction of fecal coliforms does not necessary predict reduction of other, more resistant pathogens, which also must be considered with respect to handling safety and disposal of composted biosolid waste.

In dry-sanitation systems, pathogenic microorganisms can be reduced through biodegradation, desiccation, or a combination of the two (5). In this study, desiccation was found to be the principal method for fecal coliform reduction for two reasons. First, the greatest number of samples (54%) had low moisture content, which was suboptimum for biodegradation, and of these, 73.8% were class A. Second, only a few samples with optimum moisture for aerobic biodegradation were class A (<10%).

Desiccation occurs when moisture content is too low for microorganism survival and when cells die due to lack of water to drive cellular metabolic processes. On the other hand, aerobic biodegradation occurs when microorganisms have sufficient water for metabolic processes but is inhibited when too much water excludes oxygen. When oxygen levels are too low, anaerobic biodegradation takes over. Thus, a critical variable in this study was moisture content, which regulated the primary method (desiccation, aerobic biodegradation, or anaerobic biodegradation) responsible for fecal coliform reduction.

In this study, there was a highly significant correlation between the orientation of the SIRDO unit's solar panel (solar exposure) and higher compost classification (lower fecal coliform counts). The solar panel was in an optimal position if it faced south and was not shaded by trees and buildings. The most probable reason for the strong relationship between solar exposure and lower fecal coliform counts was that solar exposure heated the SIRDO chamber, promoting fecal coliform reduction by desiccation. With a lower percentage of water, cells were killed and biosolid classification was higher. Thus, rather than solar exposure promoting aerobic biodegradation by raising the pile temperature, the main effect was drying. Results showed that already by 3 months, more than half of the biosolid piles had less than 40% moisture.

The environmental setting of this study area was a key variable related to moisture levels of composting heaps. Summer months are hot and dry, while winter months are sunny, dry, and cool. With a year-round dry climate, moisture levels in the compost heap are lower than would be expected in humid, tropical environments. Maintaining sufficient moisture levels for aerobic biodegradation required that SIRDO managers (usually the women of the households) be able to judge moisture levels of the compost heap and adjust with water. This was usually beyond the expertise of these first-time users and may be a barrier to adequate maintenance for optimal biodegradation. As a result, at both 3 and 6 months, the moisture content of more than half the SIRDOs was <40%.

Aerobic biodegradation has the advantage of achieving high temperatures, which will destroy many pathogens that desiccation cannot (3). In this study, aerobic biodegradation was rarely (if ever) achieved for several reasons: (i) the heap's small mass was not large enough to trap sufficient heat (heat buildup) to maintain the high temperatures (40 to 60°C) required for aerobic thermophilic bacterial growth, (ii) users did not regularly adjust the moisture levels of the compost pile with water or soak materials (sawdust), and (iii) users did not regularly adjust pile oxygen content by stirring or turning over the pile.

The ideal C:N ratio for composting toilets is between 15:1 and 30:1 (5). Human excreta generally have a C:N ratio of 5:1 (8); therefore, a carbonaceous material (bulking agent or soak material) must be added after each use to raise the carbon level. The C:N ratio was not problematic in this study, as participants faithfully added sawdust (perhaps too much) after using the facilities. Undoubtedly, they were motivated to do this as the carbonaceous material covered the waste, reduced odors, and lowered the prevalence of insects. The addition of soak material also aided in aerating the compost heap by creating a coarse matrix, which allows for small air pockets. On the other hand, too much soak will lower moisture content below the optimum for aerobic biodegradation.

In the dry atmosphere of north-central Mexico, perhaps desiccation is the best mechanism for dry sanitation. The alternative of maintaining sufficient moisture content for biodegradation may not be practical and achievable for the targeted population of dry-sanitation users. Study limitations includ ed missing cases due to the inability of researchers to collect samples; thus, there were fewer 3-month samples. Since SIRDO biosolid waste will not be tested on a regular basis before disposal, it will not be possible to determine classifications. Therefore, the recommendation for users is that compost not be used before 6 months and that no 6-month compost should be disposed on edible plants or in areas where persons could be exposed via dust or direct contact.

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