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How effective is a composting toilet system for protecting human health in an emergency context?

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ABSTRACT

The Wellington Region is highly vulnerable to large earthquakes as it is crossed by active faults. Expected timeframes of 1 to 2 years for the re-establishment of networked wastewater management services provide urgency to the consideration of emergency sanitation options for the city. Lessons about emergency sanitation after the 2011 Christchurch and 2016 Kaikōura earthquakes may not be applicable to Wellington, as isolation of households, lack of road access, and inability to dig pit latrines or long drops are likely to be much greater factors and imply that human faecal waste may have to be managed completely onsite.

The objective of this study was to investigate whether an experimental composting toilet system could effectively reduce the pathogen load of human faecal matter and generate compost that could be managed safely onsite. The variables investigated were two different carbon additives from readily available plant material, and the presence or absence of a compost activator.

This experiment demonstrated that it was possible to set up a simple emergency composting toilet system able to significantly reduce human health risk associated with human faecal material (measured by the presence of the pathogen indicator bacteria *E. coli*) over a two-month period to comply with the New Zealand standard for microbiological safety for composts, soil conditioners and mulches. Of the four treatments tested, the one that produced the greatest *E. coli* reduction (7 $\log_{10}$) was with pine shavings alone. These findings indicate that treated faecal waste could be managed onsite using the normal precautions for handling potting mix.

1 INTRODUCTION

Being crossed by on- and offshore active faults, the Wellington Region is highly vulnerable to large earthquakes, with a ~10% likelihood of a magnitude 7.5 earthquake occurring in the region within the next 100 years (Rhoades et al. 2011). Recent models of infrastructure outages (Wellington Lifelines Group 2019) showed worst case scenarios of outages greater than two years for the wastewater collection and treatment network in some areas of the Wellington region. While attention has been paid to the broader consequences of earthquake damage to road, electricity and water supply networks (Cousins et al. 2014), the consequences of wastewater network damage for public health, environmental health and habitability of homes remain largely unknown for Wellington City (Stewart et al. 2019). Damage to water supply and wastewater reticulation systems provides a pathway for pathogens into water supplies (Dell and Williams, 2011). This caused a high risk of gastroenteritis outbreaks after the Christchurch earthquakes in 2010 and 2011 (Cubrinovski et al., 2014). Providing people with access to basic sanitation is fundamental for public health and to ensure the resilience of the communities following these damaging events.

Many of the emergency sanitation options used after the Christchurch earthquake were successful because the city was not isolated, its interconnected road network remained largely functional and its airport was reopened less than six hours after the February 2011 earthquake. Prolonged isolation of parts of the city is likely to be a much greater factor for Wellington households, due to the potential for widespread landslides in hill suburbs affecting road access. This in turn implies that human waste will have to be managed onsite as emergency sanitation options such as chemical toilets rely completely on road access for delivering chemicals and collecting waste. While some progress has been made on options such as emergency composting toilets (WREMO 2013), significant knowledge gaps remain on how to safely manage waste onsite.

QuakeCoRE - funded research on post-earthquake emergency sanitation options is underway on two fronts: 1) investigating options for safe and self-sufficient management of human faecal waste using composting toilets, and 2) initiating conversations on emergency sanitation among researchers, emergency managers, wastewater managers and other practitioners (Brenin et al., 2020). This paper is focused on the first of these topics. The objective of the study reported here was to determine whether a composting toilet system could effectively reduce the pathogen load, and therefore the human health risk of human faecal matter and generate compost that could be managed safely onsite. The variables investigated were two different carbon additives in the form of readily available plant material, and the presence or absence of a compost activator.

2 MATERIALS AND METHODS

2.1 The composting toilet unit

Nine composting toilets were purpose-built for this experiment. They were made of plywood with a standard toilet seat and a 20 L bucket, similar to the ones used in the previous acceptability trial (WREMO 2013). Composting toilet systems are usually based on separating urine and faeces into two buckets, because, in normal circumstances, urine does not contain pathogenic organisms and it is safe to apply it to the garden. For this trial only a single bucket system just for faeces was used. Next to each toilet unit, a container of either wood shavings or woodchips (as the carbon additive) with a 675 mL scoop was provided (Fig. 1 A). The toilets were set up in seven homes and two places of work. All toilets were located adjacent to existing toilets in bathrooms, so that urine could be diverted to the existing toilet, and also so that regular handwashing facilities were available. Participants for this trial were selected because of an interest in composting toilets or emergency preparedness. Families with children under 16 year were excluded, as reviewed and approved the Massey University Human Ethics Committee: Southern A, Application 19/49. A brief demonstration was given to all users (Fig. 1 B).

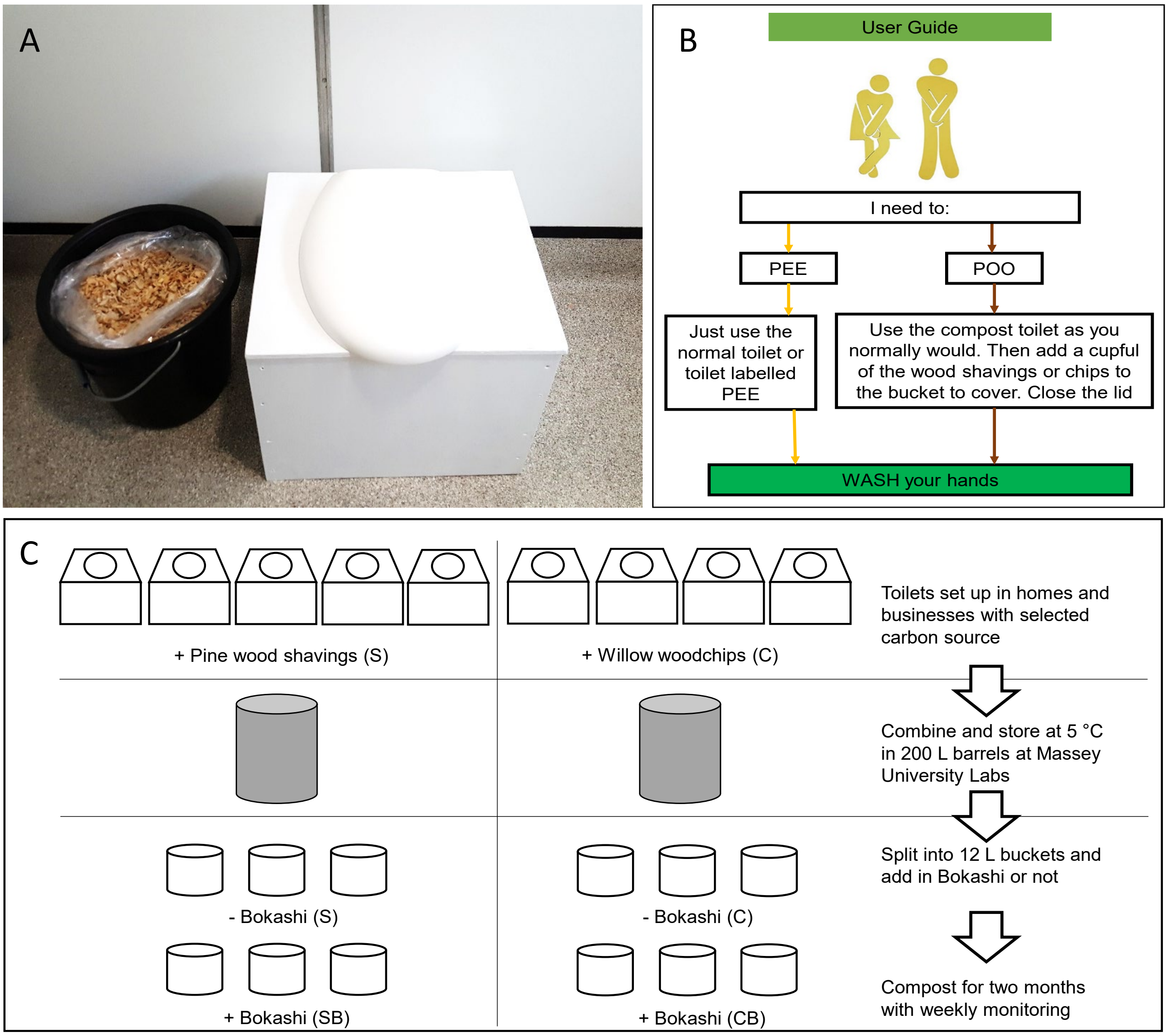

Figure 1: A: installed composting toilet and carbon source bucket. B: instructions to trial participants. C: experimental design and setup.

2.2 Experimental design and monitoring

The experimental variables were a) the type of carbon additive and b) the presence or absence of a compost activator (Fig. 1 C). The selection of carbon source additives was based on what could be practically supplied to the population in Wellington following a large earthquake. The rate of application was calculated for each carbon additive to result in a C:N ratio of approximately 20 (Bernal et al. 2009). The two additives and rates of application selected were: i) Pine (*Pinus radiata*) wood shavings. Wood was untreated and machined with a woodworking thicknesser to produce a fine shaving approximating what would be produced at scale from a larger timber processing plant. Their moisture content was 16.7%, with a total carbon and nitrogen content of 18.4% and 0.001% respectively, giving a very high C:N ratio of 18,400. Each 675 mL scoop contained 50 g of pine shavings. ii) Willow (*Salix cinerea*) woodchips. The woodchip was harvested and put through a chipping machine 2 weeks prior to use and left in a pile, to replicate the likely conditions in a disaster situation. Their moisture content was 33%, with total carbon and nitrogen contents of 47% and 0.56 % respectively and C:N ratio of 84. Each 675 mL scoop contained 125 g of willow woodchips.

Bokashi was added as a compost activator to determine whether, under the conditions of the experiment, it would have a positive impact on the die-off rates of the indicator organism *Escherichia coli*. Bokashi is a dry form of the so-called "effective microorganisms" inoculated in wheat bran and fine wood chip, which are claimed to enhance treatment of sewages or effluents (Namsivayam et al, 2011). Although the exact composition is unknown due to trade mark, it mostly consists of lactic acid bacteria, photosynthetic bacteria, yeast, fermenting fungi and actinomycetes (Namsivayam et al. 2011). Bokashi was sourced from ZingBokashi in Christchurch, and added at 5% of the total weight of combined waste and cover material.

A scheme of the experimental design is shown in Fig. 1C. Five toilets received pine wood shavings, and four willow woodchips. The faecal waste was collected over a 12-day period with toilet buckets being exchanged out as required. Any collected waste was stored at 5 °C in two 200 L barrels during this period, to impede the composting processes until the beginning of the experiment. At the end of the collection period (Day 0 for testing), the waste in each large barrel was weighed, mixed thoroughly, and split into 12 20 L buckets. Bokashi was added to half the buckets at 5% w/w. The buckets remained in the lab at 18 °C with the lids slightly open to allow the circulation of oxygen. The composting material was sampled at days 0, 3, 7, 14, 21, 28, 35, 42, 49, 56 and 63 after mixing the contents of bucket with a stirrer for 10 min to ensure homogeneity. All samples were analysed for *E. coli* and moisture. In addition, on days 0, 21 and 63, samples were also analysed for total carbon and nitrogen, inorganic nitrogen, total and water-soluble phosphorous.

2.3 Monitoring human health risk and chemical analysis

The human health risk associated with the composting faecal material was determined by measuring the indicator bacteria *E. coli*, which is a type of bacteria commonly found in the guts of warm-blooded mammals (including people) and birds. It is used as an indicator for the presence of disease-causing organisms. *E. coli* were enumerated using a five-tube Most Probable Number (MPN) method. Moisture was determined after oven-drying the sample at 104 °C. Total nitrogen (TN) and carbon (TC) were analysed with an Elemental Combustion Analyser (Elementar). Inorganic nitrogen (NO_3^--N and NH_4^+-N) was determined by a Flow Injection Analyser (Lachat) after a 30 min water extraction. Total phosphorus (TP) was microwave digested (Milestone UltraWAVE) and water-soluble phosphorus (WSP) was water extracted for 30 min, and in both cases analysed by a colorimetric determination. All determinations were performed by Eurofins ELS Ltd. (Lower Hutt, New Zealand).

2.4 Data analysis

Moisture, TC, TN, TP and C:N ratio data were subjected to analysis of covariance with type of carbon additive, Bokashi and day as independent variables. The assumptions of normality, homoscedasticity and linearity were assessed by plotting the residuals of the model. NH_4^+ and WSP did not fulfil the linearity, homoscedasticity or normality assumptions so were analysed by Kruskal-Wallis non-parametric test for each day. As MPN data do not represent real values but most probable numbers, parametric tests are not appropriate. Instead, a range of non-parametric tests were performed to assess the results: the medians in each day and treatment were analysed by non-parametric Friedman's test, the differences between treatments in each day were assessed by Kruskal-Wallis, and the overall differences between treatments –disregarding days – by pairwise Wilcox rank test with the Holm p-value adjusted method. The analysis were performed with the *stats* package of the programme R (R Core Team 2018).

3 RESULTS AND DISCUSSION

3.1 *Escherichia coli* die-off

E.coli reductions over the course of the experiment are shown in Fig. 2. The type of carbon additive was the main factor affecting the die-off of *E. coli*, with a faster reduction when pine shavings were added to the faecal material. Bokashi addition did not provide any benefit. After the two months of experiment, the *E. coli* in waste with pine shavings without Bokashi decreased to 2 MPN/g, however it only decreased to 330 MPN/g when Bokashi was added. There were no differences between willow woodchips with or without Bokashi, but there were significant differences between all the other treatments. Exponential models indicated a reduction of *E. coli* to 100 MPN/g around day 55 for pine shavings alone ($R^2 = 0.88$), and around day 92 with addition of Bokashi ($R^2 = 0.69$). *E. coli* below 100 MPN/g indicate that the material is safe to be applied to the soil (Compost New Zealand 2007). Results with willow woodchips could not be fitted to exponential models ($R^2 < 0.1$).

In a conventional composting process (Bernal et al., 2009) and commercial composting toilets (Anand & Apul, 2014), temperature (> 55ºC) is the main factor ensuring a reduction of pathogens. Temperature was not measured in this experiment, but it is unlikely that the amount of material composting in the experimental buckets reached the required temperature for reducing the pathogens. In that case, a similar reduction should have occurred in the rest of the treatments. Moisture is also usually related to *E. coli* survival (Hill et al. 2013). However, in our experiment there was no relationship between *E. coli* and moisture. For our experiment, we propose that composition of pine shavings themselves could be responsible for the reduction of *E. coli*, since pine wood contains high concentration of terpenes, which are known for their antimicrobial properties (Vilanova et al. 2014). Alternatively, high concentration of NH_3 inhibits certain microorganisms in the compost (Hill et al. 2013), and this could be a reason for *E. coli* reduction in our experiment. Despite these promising results, caution is required before drawing conclusions about eliminating health risk. As explained in the next section, it is unlikely that the material was completely stable, and regrowth of pathogens is a potential risk that needs further investigation (Horswell & Hewitt 2014).

3.2 Composting parameters and stability

Pathogen reduction was the main endpoint to assess the human health risk of the waste materials in emergency composting toilets. However, if the material had not been sufficiently stabilised during the composting process (i.e all the easily assimilable carbon used), it is possible that the material could support the re-growth of pathogens (Horswell & Hewitt 2014).

Moisture of the waste is an important factor affecting the composting process, including composting toilets (Anand & Apul, 2014; Bernal et al., 2009). In our experiment, moisture was significantly affected by both type of carbon additive and Bokashi addition (Table 1), in the order CB > C > SB > S. Moisture significantly decreased over the course of the experiment (Fig. 3 right) at similar rates in all the treatments, since there was not significant interaction between treatments and day (Table 1). The moisture contents throughout the

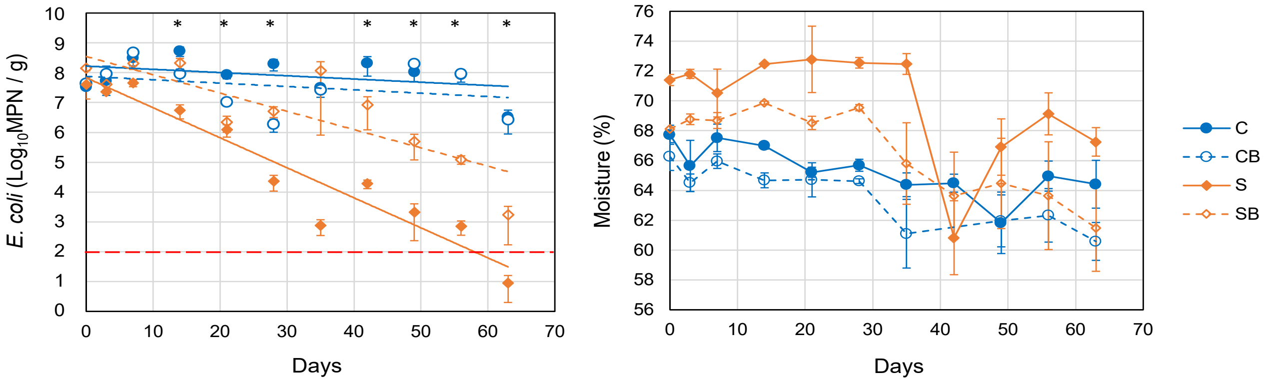

*Figure 2: Left: E. coli enumeration during the experiment and fitted exponential models. Red dotted line indicates levels considered safe to be applied to soil (100 MPN/g), * Significant differences between treatments (Kruskal-Wallis p < 0.05). Right: Moisture of the compost during the experiment. Results are means and standard errors. C: willow woodchips, S: pine shavings, B: Bokashi*

Table 1: P values of the ANCOVA showing which factors, or interaction between them, significantly affect the results of moisture, total carbon, total nitrogen, C:N ratio and total phosphorous.

Factors	**Moisture**	**TC**	**TN**	**C:N**	**TP**
C source	0.000 ***	0.346	0.0784 °	0.018 *	0.000 ***
Bokashi	0.000 ***	0.875	0.2152	0.072 °	0.158
Day	0.000 ***	0.000 ***	0.000 ***	0.019 *	0.135
C source * Bokashi	0.164	0.901	0.178	0.130	0.795
C source * Day	0.146	0.935	0.0867 °	0.107	0.053 °
Bokashi * Day	0.340	0.571	0.5437	0.390	0.921
C source * Bokashi * Day	0.998	0.658	0.584	0.713	0.362

*** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, ° $p < 0.1$

experiment were considerably higher than the optimal for composting (50 – 60 %, Anand & Apul (2014)), which had the potential to cause anaerobic conditions (Bernal et al., 2009). Aeration is also a key factor of the composting process (Anand & Apul, 2014; Bernal et al., 2009). Although there was not an aeration system in this experiment, the weekly blending prior to sampling, and lids being left slightly open, provided some aeration which contributed to some organic matter decomposition, as shown by TC results.

TC significantly decreased (10 % loss) over the experimental period (Fig. 4), however there were no significant differences between treatments (Table 1). TN also decreased over the experimental period (Fig. 4), which was slightly influenced by the type of carbon added ($0.05 < p < 0.1$). TN decreased about 27 % when carbon additive was pine shavings, and about 17 % when it was willow woodchips. This difference in C and N reduction produced a significant difference in the C:N ratio, which increased over the experiment, with differences between carbon additive and Bokashi addition (Table 1 and Fig. 3).

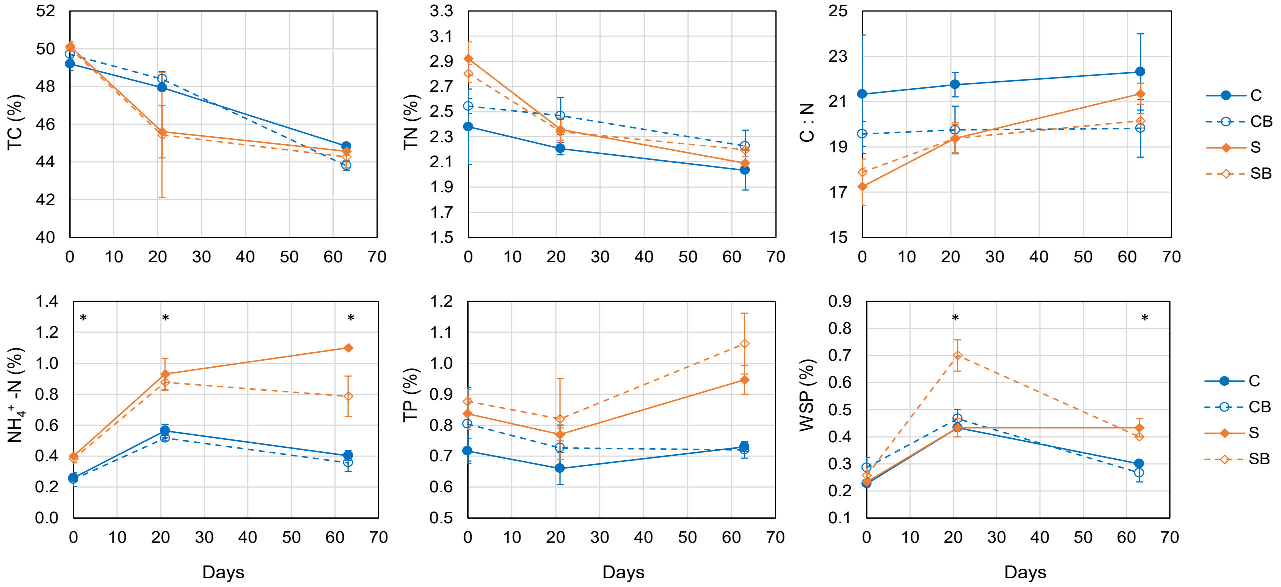

*Figure 3: Average and standard errors of total carbon, total nitrogen, C:N ratio, ammonium, total and water soluble phosphorus on day 0, 21 and 63 of the experiment. C: willow woodchips, S: pine shavings, B: Bokashi. * indicate significant differences between treatments in those days (Kruskal-Wallis $p < 0.05$).*

Contrary to the common composting process, with an increase in C:N due to mineralization of organic matter (Bernal et al., 2009), in this experiment the loss of nitrogen was faster than the loss of carbon, and it depended on the carbon additive added. NH_4^+ increased faster during the first month until day 21, with significant differences between treatments (Fig. 4, Kruskal-Wallis $p < 0.05$).

NH_4^+ was higher in waste with pine shavings than with willow woodchips, which relates to a faster loss of nitrogen when pine shavings are added. Given the high moisture content, we cannot discount the presence of some anaerobic microsites in the composting buckets, which would favour the loss of nitrogen by denitrification (Bernal et al., 2009). Volatilization of ammonia is also a possibility given the high NH_4^+ concentration. In any case, any of these processes could explain a faster loss of nitrogen compared with loss of carbon by mineralization. NO_3^- was not detected in any analysed sample, which indicated that the material was not fully composted (or stabilised) (Bernal et al., 2009). Total phosphorous was also expected to increase as the composting process proceeded (Wei et al., 2015). However, total P was only significantly affected by carbon additive, with a slight influence by the interaction between carbon additive and day (Table 1). Water soluble phosphorous, however, was more variable along the experiment and between treatments (Fig. 3).

4 CONCLUSIONS

This experiment demonstrated that it is possible to set up a very simple emergency composting toilet system able to achieve a significant reduction in the human health risks associated with the composting of human waste. Such system will increase the resilience of people are affected by interruptions in wastewater network collection after a major earthquake and contribute to the public health of the affected communities.

The experimented emergency composting toilet which used pine shavings alone produced the greatest *E. coli* reduction (7 $\log_{10}$), and the treated faecal waste complied with the New Zealand standard for microbiological safety for composts, soil conditioners and mulches. These findings indicate that treated faecal waste could be managed onsite using the normal precautions for handling potting mix. Given that it is unlikely that this experiment followed a conventional composting process (with increasing temperatures up to 65 °C for certain periods of time, oxidation and stabilization of the organic matter), as shown by chemical analysis (TC, TN, C:N, NH_4^+ and NO_3^-), the reduction of pathogens could be a consequence of either the antimicrobial properties of pine shavings and or an increase in toxic ammonia formation. This suggested that the final compost was not stable (or mature) and that there may be the potential risk of re-growth of pathogenic organisms. Further research is required to investigate the potential regrowth of *E. coli* or other pathogenic organisms after the compost is applied to the soil.

Only the risk related to pathogen load is discussed in this work. Multiple dimensions should be considered when deciding if it is "safe" to manage this type of waste onsite. Reaching maturity in the compost material (in contrast with just stability, as defined by Bernal et al. (2009)) would dictate the possibility of using the materials in home gardens – if available in the dwellings – without negatively affecting the soil and vegetation. In addition, further consideration of cultural and social sensitivities related with the management of human waste will also change the vision of what it is considered "safe" (Ataria et al., 2016).

5 ACKNOWLEDGMENTS

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