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Evaluation of Solvita compost stability and maturity tests for assessment of quality of end-products from mixed latrine style compost toilets

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ABSTRACT

It is challenging and expensive to monitor and test decentralized composting toilet systems, yet critical to prevent the mismanagement of potentially harmful and pathogenic end-product. Recent studies indicate that mixed latrine composting toilets can be inhibited by high ammonia content, a product of urea hydrolysis. Urine-diverting vermicomposting toilets are better able to accomplish the goals of remote site human waste management by facilitating the consumption of fecal matter by earthworms, which are highly sensitive to ammonia. The reliability of Solvita® compost stability and maturity tests were evaluated as a means of determining feedstock suitability for vermicomposting (ammonia) and end-product stability/completeness (carbon dioxide). A significant linear regression between Solvita® ammonia and free ammonia gas was found. Solvita® ranking of maturity did not correspond to ranking assigned by ammonium:nitrate standards. Solvita® ammonia values 4 and 5 contained ammonia levels below earthworm toxicity limits in 80% and 100% of samples respectively indicative of their use in evaluating feedstock suitability for vermicomposting. Solvita® stability tests did not correlate with carbon dioxide evolution tests nor ranking of stability by the same test, presumably due to in situ inhibition of decomposition and microbial respiration by ammonia which were reported by the Solvita® CO_2 test as having high stability values.

1. Introduction

Public composting toilets (CTs) are commonly used in North America to collect and treat latrine waste mixed with carbonaceous bulking agent at decentralized sites such as national, provincial, and state parks in Canada and the United States. Hill and Baldwin (2012) documented highly variable end-product stability, maturity, hygiene and consistent failure of in-field systems to meet the only relevant standard, National Standards Foundation Standard 41 (National Standards Foundation, 2011) for non-liquid-saturated treatment systems. Further investigation by Hill et al. (2013b) indicated that ammonia from urine had a strong inhibitory effect on the composting process. Indeed, remote public toilets that diverted urine away from feces, and did not use a bulking agent, produced end-product, which was consistently low in *Escherichia coli*, highly stabilized and mature (Hill and Baldwin, 2012). This indicated that urine-diversion is an important feature to incorporate in the management of remote site toilets. To ensure the efficacy of remote composting toilets of any type so as to avoid inhibitory conditions and produce stabilized and mature end-products, reliable testing is needed (Willetts et al., 2007). Then, different approaches to waterless human waste management can be evaluated and compared and, by using valid benchmarks, they can be optimized and improved.

The Standard 41 stipulates the following indicators of CT compost quality: low moisture content, low fecal coliform counts, and no odor. In this context, quality measures the ease and safety of handling and disposing of the composted material. Odor is related to ammonia content and thereby linked to end-product maturity, in that all the ammonia is expected to eventually oxidize to nitrate as a result of effective composting. A mature end-product is one that is ready to be re-used or safely disposed of Wichuk and McCartney (2010). But odor measurement is qualitative and a highly subjective indicator of maturity. Compost stability refers to the degree of decomposition achieved with stable material having very little microbial activity (Wichuk and McCartney, 2010). No index of stability is included in the NSF Standard 41. Unstable material could be subject to further degradation producing heat, gases and potentially disease-causing vectors (Mathur et al., 1993). In large commercial composting industries, quantitative and reproducible indices of end-product stability and maturity have been well documented (Wichuk and McCartney, 2010). National Standards Foundation Standard 41 is currently under

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revision and additional measures of stability and maturity are very much needed.

Woods End Labs Inc. (Mount Vernon, Maine, USA) manufactures Solvita® tests for the assessment of compost stability by means of a carbon dioxide sensitive colorimetric gel and compost maturity by means of a ammonia gas sensitive colorimetric gel (Brewer and Sullivan, 2001). Both colorimetric gels are interpreted with a number scale (1–8 for stability and 1–5 for maturity) where higher numbers indicate greater stability/maturity. The Solvita® test is widely accepted by the international compost industry and is uniquely recognized as suitable for onsite measurements and immediate results (Wichuk and McCartney, 2010). Because many CTs in North America are found in remote locations and are maintained by unskilled operators, this feature of the Solvita® test makes it one of the more promising tools for onsite measurement and analysis of CT end-product. The reliability of the Solvita® test depends on the conditions under which it is used, since factors such as moisture content, temperature, ammonia and type of organic matter can affect the results (Seekins, 1996; Brewer and Sullivan, 2001). Solvita® was used to measure stability in urine diversion dehydrating toilet (UDDT) fecal material and was in poor agreement with measured CO_2 mineralization rates (McKinley et al., 2012). The Authors argued that discordance between the fecal matter C:N ratio and that used to calibrate the Solvita® test was to blame. According to our knowledge, Solvita® tests have not been tested and validated yet for evaluating (non-urine diversion) CT end-product, which has very different properties than conventional compost.

It was the objective of this study to evaluate the ability of Solvita® compost stability and maturity indicators to predict standardized laboratory carbon dioxide evolution and un-ionized ammonia gas concentration in end-product from public composting toilets. Additionally, Solvita®'s accuracy in ranking stability and maturity into commonly used categories of 'very mature/stable', 'stable/mature', and 'unstable/immature', were compared to standardized ranking of stability by carbon dioxide evolution and maturity by the ammonium-N:nitrate-N ratio, two widely accepted benchmarks (Wichuk and McCartney, 2010).

If the test accurately reflects the state of stability and maturity, and provides insight into material safety, it may become an inexpensive and valuable tool in the challenging certification of CTs by NSF. It can be used to assess CT feedstock suitability (primarily in relation to ammonia concentration as affected by urine) and end-product stability and maturity prior to handling for extraction. This could lead to improved management of the currently poorly performing CTs and a reduction in the risks and consequences associated with discharging incompletely composted, immature or unstable human biosolids.

2. Methods

2.1. Locations

A total of 11 locations operating public mixed latrine style composting toilets (CTs) were visited in Washington (USA) and British Columbia, Alberta, and Northwest Territories (Canada) between 2009 and 2011. Nine were found in remote national, provincial, and regional park sites. Two were found in public buildings; only one site was housed within a heated utility room. The locations' elevations ranged from 50 to 2100 masl and between 46°N and 61°N in latitude. The locations experienced between 500 and 45,000 uses per year per toilet with a concentration of usage in summer months and minimal usage during winter months except at the toilet within the public building where usage was more consistent throughout the year. A summary of site characteristics can be found in Hill and Baldwin (2012).

2.2. Composting chambers

A total of 15 composting chambers were investigated at the 11 locations. All toilets sampled were commercial units that had been sized and installed professionally. Despite some differences in tank size, all systems were used and maintained in a similar fashion by each agency according to operational manuals provided at the time of purchase. Both fecal matter and urine were added through the toilet hole. Pine shavings or peat moss bulking agent (40–200 ml) were added with each use along with toilet paper. During maintenance, additional bulking agent was added if the material was deemed too wet, a judgment likely to differ considerably by operator. When a chamber was filled up, end-product was removed from the bottom. A description of compost toilet chamber design and characteristics can be found in Hill and Baldwin (2012).

New chambers were started 2/3–3/4 full with bulking agent. Depending on use, chamber size, and operational procedures, this bulking agent will dominate the material removed for 1–8 years before true 'end-product' (fecal matter, trash, 'compost') would be observed. Only samples from the oldest end products in each chamber were investigated. The materials sampled were deemed 'finished' end-products as all material was older than six months up to eight years, which is in accordance with NSF/ANSI Standard 41 (National Standards_Foundation, 2011), where testing of end-products from in-field systems is made after six months of system operation.

2.3. Samples

Two to five samples were extracted from each compost chamber as determined by the funding available, which was provided on a location-by-location basis. Material was removed with a gloved hand from the oldest sections of the material pile and the sample material was placed into sterile glass jars, following the procedures according to the NSF/ANSI Standard 41(National Standards Foundation, 2011). Glass jars were shipped in a cooler with ice packs by overnight courier to the commercial laboratory for analysis. In the majority of cases the laboratory received samples within 48 h after sampling. In a few instances samples arrived up to 72 h after sampling.

2.4. Biochemical analyses

Solvita® stability and maturity tests were conducted at room temperature within 12 h of sampling according to the instruction manual (Woods End, 2000). Moisture content was adequate as determined by a squeeze test. Benchmark Laboratories Ltd. (Bay 2, 3419 12th St. NE Calgary, AB), an ISO 17025 accredited analytical laboratory, analyzed solid end-product samples for: carbon dioxide evolution by Test Methods for the Examination of Composting and Compost (TMECC, US Composing Council http://compostingcouncil.org/tmecc/) 05.08-B method, un-ionized ammonia-N by cold-water-shake (1:2 sample:water) followed by measurement with an Orion high-performance ammonia electrode (Thermo Fisher Scientific, Beverly, MA) at 20 °C according to the manual's instructions for free ammonia concentrations of >1 ppm, pH by cold water shake (1:2 sample:water) followed by measurement with VWR Symphony pH probe at 25 °C, and nitrate by American Public Health Association (APHA) Method 4110A. Ammonium-N was calculated at 20 °C according to the pH and a pKa value for ammonia/ammonium equilibrium of 9.3. Benchmark Laboratory (Calgary) Inc. either processed samples immediately upon receipt or after 24–48 h storage at 4 °C. All values reported in dry solids.

2.5. Statistics

No adjustments were made to the data set except where noted specifically in the results. JMP version 10 (SAS® 2009) was used to produce all graphical displays and regression statistics. The total sample size was 36, but not all samples were analyzed for all parameters due to budget constraints and the high cost of some procedures, such as carbon dioxide evolution and so some data comparisons are made with fewer samples as noted in the text.

3. Results

3.1. Maturity

Solvita® NH_3 values were significantly predictors of free ammonia gas concentrations ($n = 36$, $p < 0.001$, $r^2 = 0.50$, NH_3–N (mg/kg ds) = 1700–353*Solvita-NH_3 value) (Fig. 1). However, there was a wide range of ammonia gas concentrations recorded (232–2767 mg/kg NH_3–N and 116–1387 mg/kg NH_3–N) for immature-rated Solvita® ammonia test levels 1 and 2 respectively. The majority of samples (25/36) were categorized as immature by Solvita® ranking (1–3).

The dashed line plotted on Fig. 1 at 500 mg NH_3–N/kg ds represents the free ammonia concentration above which toxic effects on earthworms have been recorded (Edwards and Neuhauser, 1988). The following fractions of samples (and percentages) were found below this toxic threshold for each of the Solvita® ammonia values (1–5 respectively): 2/15 (13%), 2/6 (33%), 2/5 (50%), 4/5 (80%), and 6/6 (100%).

The ammonium-N:nitrate-N ratio is used as an index of maturity (Wichuk and McCartney, 2010) since effective composting should result in an concomitant increase of nitrate with decrease in ammonia due to sufficient aerobic microbial activity. The ammonium-N:nitrate-N ratio was plotted against the Solvita® ammonia rank in order to compare Solvita®'s ability to match this maturity index ($n = 30$, Fig. 2). There was no significant linear or semi-logarithmic relationship between the Solvita® ammonia rank and the ammonium-N:nitrate-N ratio. As per TMECC 05.02-C, the ammonium-N:nitrate-N maturity index ranked zero samples as 'very mature', two samples as 'mature', and the rest (28) as 'immature'. Solvita® ammonia tests ranked four samples as 'very mature', three as 'mature', and 23 as 'immature' (TMECC 05.08-E). The percentage of samples Solvita® accurately ranked in relation to ammonium-N:nitrate-N ranking was: 0% for 'very mature', 0% for 'mature' and 82% for 'immature' (23/28).

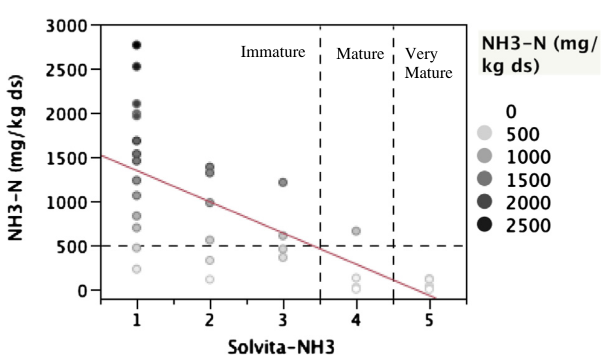

Fig. 1. Solvita® ammonia values plotted against corresponding free ammonia gas concentrations in public composting toilet end-product samples. Solid line is line of best fit (linear regression). Vertical dashed lines represent maturity divisions. Horizontal dashed line represents toxicity threshold of free ammonia to earthworms.

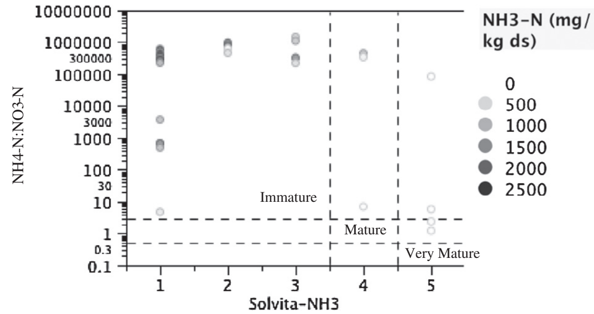

Fig. 2. Solvita® ammonia values plotted against ammonium-N:nitrate-N maturity index. Dashed lines represent maturity divisions. Plot area where divisions overlap are labeled with the corresponding maturity label.

3.2. Stability

Solvita® carbon dioxide values were compared with carbon dioxide evolution results from the laboratory measurements ($n = 21$) (Fig. 3). There was no clear or significant relationship between these two methods of assessing stability. Carbon dioxide evolution rate ranked 16 samples as 'very stable' (< 2 mg CO_2/g OM/d), five samples as 'stable' (2–4 mg CO_2/g OM/d), and 0 as 'unstable' (>4 mg CO_2/g OM/d) as per TMECC 05.08-B. In contrast, based on TMECC 05.08-E, the Solvita® carbon dioxide test ranked only one sample as 'very stable (7–8), 18 samples as 'stable' (5–6), and 2 samples as unstable (1–4). There were no matches between stability indices in the 'very stable' rank, an 80% match by Solvita® of 'stable' ranking CO_2 evolution (4/5), and a 0% match

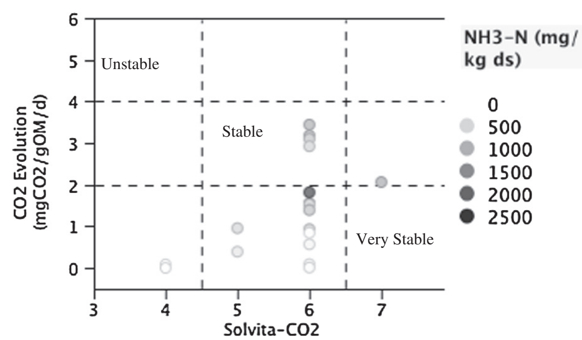

Fig. 3. Solvita® carbon dioxide stability values plotted against carbon dioxide evolution test results. Dashed lines represent stability divisions. Plot area where divisions overlap are labeled with the corresponding stability label.

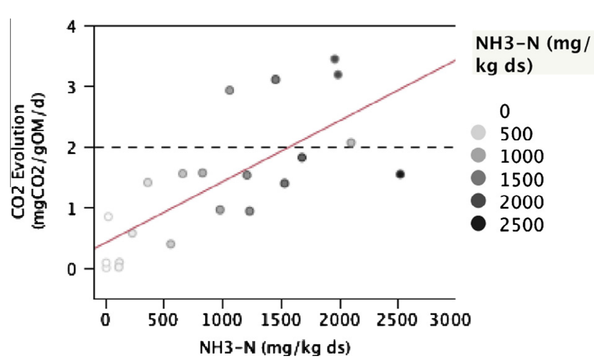

Fig. 4. Free ammonia values plotted against corresponding carbon dioxide evolution results. Solid line is the line of best fit (linear regression). Dashed line represents stability division.

in the 'unstable rank'. There a match of 4/5 mature ranking CO_2 evolution samples by Solvita® samples, there were another 14 Solvita® samples assigned 'mature' rank which were categorized as very mature (<2 mg CO_2/g OM/d). In Fig. 3, samples were shaded according to free ammonia concentration, which at high concentrations, is known to have an inhibitory effect on in situ decomposition. A vertical gradient in ammonia concentration is apparent (Fig. 3).

Free ammonia was plotted against carbon dioxide evolution in order to explore ammonia's potentially inhibitory effect (Fig. 4). The ability of free ammonia concentration to predict carbon dioxide evolution was significant ($n = 21$, $r^2 = 0.54$, $p < 0.0001$, CO_2 Evolution (mg CO_2/g OM/d) = 0.41 + 0.0010*NH_3–N (mg/kg)).

4. Discussion

There are two management tasks associated with the operation of public composting toilets, which would benefit from a simple, robust, and inexpensive stability and maturity assessment test. These tasks are (1) the evaluation of feedstock suitability and (2) the evaluation of process and end-product completeness.

4.1. Feedstock suitability

Lay literature and manufacturer instructions on the operation of mixed latrine style composting toilets place great importance on the ratio of carbon to nitrogen, the moisture content, and loading rates (Snohomish Health District, 2004). These parameters are not easily determined without the necessary equipment and laboratory procedures. Regardless, many mixed latrine-style composing toilets do not create the optimum composting conditions as per national regulations (EPA, 2007), subsequently fail to produce compost as per commonly accepted definitions, fail to meet the currently limited NSF Standard 41 criteria, and are ten times more expensive and hazardous than their European, urine-diverting, vermicomposting toilet counterparts (Hill and Baldwin, 2012). Urine-diversion accomplishes two objectives: (1) rapid elimination of the major volume of the excrement stream and odor producing ammonia nitrogen and (2) production of a low ammonia fecal material that can be inhabited and consumed by earthworms, which are highly sensitive to ammonia with toxic thresholds starting at 500 mg/kg ds (Edwards and Neuhauser, 1988; Domínguez, 2011). Only 13% of samples having a Solvita® ammonia value of 1 had <500 mg/kg ds NH_3–N and 100% of samples having the Solvita® ammonia value of 5 had <500 mg/kg ds NH_3–N. This indicates that Solvita® ammonia tests could be employed to evaluate the suitability of fecal material as feedstock for vermicomposting where material having Solvita® ammonia value 1 will be toxic to earthworms and Solvita® ammonia value 5 will be absent in this toxic substance making it potentially suitable for vermicomposting. Other feedstock characteristics such as moisture content must also be suitable for worm inhabitation, but on average, human fecal matter meets these requirements (Yadav et al., 2010). There is little literature reporting on the use of Solvita® tests to measure feedstock suitability either for composting or for vermicomposting. In large scale compost operations, is more common to lack sufficient nitrogen and in a worse case scenario, excessive nitrogen results in odors during the rapid heating and volatilization phase of thermophilic composting, which can be managed by manipulating the carbon to nitrogen ratios (Haug, 1993). The data presented in this work indicates that most of the CTs had material that was not suitable for vermicomposting: 25/36 samples were immature according to Solvita® and most of these (19/36) had ammonia concentrations above the toxicity level for worms. Material <2 years old from in-field urine diversion vermicomposting toilets were all between Solvita® ammonia values 4–5 (Lalander and Hill, unpublished).

Solvita® ammonia tests could be used in this feedstock evaluation mode to evaluate urine-diversion efficiency, and be included in NSF Standard 41 as a simple quantitative index of performance to assess the capability of commercial products to create feedstock suitable for onsite 'vermicomposting'. The term 'compost' should be avoided for the end-product because of the inability of earthworms to destroy hookworm ova, a pathogen that resists sanitization by earthworm (Hill et al., 2013a).

4.2. End-product evaluation

Compost value is derived from a range of variables related to: (1) its benefits such as nutrient content (i.e. nitrate) and its structural porosity when applied as a soil amendment; (2) its detriments (e.g. heavy metals) when applied as a soil amendment; (3) risks to operators and users (i.e. pathogen content and vector attractant); and (4) ease of transport (i.e. limited re-heating potential, reduced volume/mass). As the end-product from public toilets is contaminated with trash and resistant pathogens, even after vermicomposing or long storage times (McKinley et al., 2012), it is unlikely to be disposed onsite or reused. But, it is important to be able to measure CT end-product stability accurately onsite to assess factors (2) and (3). Actual compost stability (CO_2 evolution rate) was not accurately determined with the Solvita® test (Fig. 3). The extremely high ratio of ammonium-N:nitrate-N found in many samples (Fig. 2) is likely caused by the high inputs of nitrogen (from urine).

At high ammonia concentrations, microorganisms less sensitive than nitrifying bacteria can be inhibited (Chen et al., 2008). Thus, the lack of any correlation in Fig. 3 can be explained in light of the Solvita® warning that high ammonia concentrations can result in microbial inhibition and false stability readings (Product Instructions, Woods End, 2000). The in situ inhibitory effect of ammonia was removed due to volatilization during the three day equilibration step necessary prior to the four day laboratory-based CO_2 evolution test (TMECC 05.08-B). As a result, samples with the highest ammonia (greatest inhibition) recorded the highest CO_2 evolution values (least stable) and the similarly, samples with lowest ammonia resulted in lowest CO_2 evolution (most stable) (Fig. 4). Due to the large number of samples with high ammonia in public mixed latrine compost toilets and limited knowledge of the threshold (and its variability) beyond which inhibition of decomposition occurs, the Solvita® stability test does not appear to have value as an end-product analysis tool for this type of toilet. Additional research should be conducted on how to adapt the use of Solvita® stability to better measure the degree of completeness. This will contribute towards estimating the amount of mass reduction (i.e. carbon mineralization) based on the stability level. Even for urine-diverting toilets, which are unlikely to have inhibitory levels of ammonia, the Solvita® stability test has not been found to be accurate (McKinley et al., 2012). Thus, there is much work to do in order to improve the calibration and operation of the Solvita® test for CTs and UDDTs.

The CO_2 evolution rates measured for these CTs, ranging between 0.00195 and 3.18 mg CO_2/g OM/day, would classify all these samples under TMECC 05.08-B as mature to very mature (Wichuk and McCartney, 2010). However, in addition to the inhibitory effect of ammonia, these values are likely diluted by the large fraction of un-decomposable bulking agent that is added with each toilet use. Samples taken from composting toilets that require bulking agent, should be sieved to remove bulking agent prior to CO_2 evolution testing in order to be able to make comparisons with accepted stability standards developed for a wide variety of feedstocks.

5. Conclusions

Solvita® maturity tests have the potential to offer considerable value and utility in the determination of fecal toilet waste suitability as feedstock for vermicomposting, which is a more efficient and effective means of managing human waste at remote toilets sites than conventional mixed latrine composting toilets. Feedstock having Solvita® ammonia value 1 will likely be toxic to earthworms, containing >500 mg/kg NH_3–N (ds). Material having Solvita® ammonia value 5 is associated with material <500 mg/kg NH_3–N (ds) which is below the toxic threshold of earthworms. The Solvita® stability test in its current form did not accurately represent CO_2 evolution and carbon mineralization, and is not recommended for assessing CT end-product stability. For the samples in this study, this was likely due to the inhibitory effect of ammonia. Modifications to the Solvita® stability test procedure are needed to make it more relevant for human fecal matter compost.

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