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Vermicomposting toilets, an alternative to latrine style microbial composting toilets, prove far superior in mass reduction, pathogen destruction, compost quality, and operational cost

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ABSTRACT

Composting toilets aim to recycle excrement into safe, stable humus. Preceding this, low costs, low risks, and mass reduction should be ensured. Source separating vermicomposting toilets (SSVCs) outperformed mixed latrine microbial composting toilets (MLMCs) in all categories. MLMCs: incurred ten times greater operational costs; created 10x more operator exposure; employed no proven pathogen reduction mechanism since solid end-products averaged 71,000 ± 230,000 CFU/g (fecal-origin) *Escherichia coli* and 24 ± 5% total solids, consistently failed NSF/ANSI Standard 41; failed to reduce volatile solids compared to raw fecal matter; increased total contaminated dry mass by 274%, and produced alkaline end-product (8.0 ± 0.7) high in toxic free ammonia (Solvita® 2.6 ± 1.5). SSVCs have low maintenance costs and risks; adequate worm density for pathogen destruction (0.03 ± 0.04 g-worm/g-material); reduced *E. coli* 200 ± 244 CFU/g in neutral (7.4 ± 0.3), stable (60 ± 10% volatile solids), and mature (4 ± 0 Solvita® NH_3) end-product.

1. Introduction

Human waste management at remote or decentralized sites is very challenging. These sites lack standard municipal infrastructure including road access, sewerage, electricity, and water supply. Without these basic services proper human waste management becomes expensive, intensive, and offensive but is essential in order to prevent occupational hazards, environmental contamination, disease transmission, and meet legal requirements. Systems with low maintenance costs are sought after and usually include a waste treatment process and onsite disposal of liquids and/or solids. However, the permitting, construction, function, and maintenance of onsite systems in remote areas can be challenging where shallow soils, steep terrain, limited vegetation, and short seasons exist (Weissenbacher et al., 2008).

Composting toilets are marketed as waterless human waste treatment systems suitable for public service at remote sites. The overall goal of most compost toilet manufacturers is to facilitate the decomposition of human waste without reliance upon the surrounding soils to the point that end-products can be safely disposed onsite without further treatment. Marketing information from compost toilet manufacturers indicates that liquid leachate and solid end-products are suitable for on-site disposal in public parks, providing an attractive alternative to the expense incurred transporting biosolids offsite for disposal or further treatment.

There are risks associated with the operation of a compost toilet which continually discharges leachate and requires the periodic discharge of solid end-product including: direct pathogen transmission during maintenance; indirect pathogen transmission by vectors to visitors or environment; phytotoxicity; immobilization of nutrients in soil, reduced oxygen supply to plant roots, and eutrophication of aquatic environments (Fuller and Warrick, 1985; Cilimburg et al., 2000; Wichuk and McCartney, 2010; Moore, 2010).

Operational hazards associated with composting toilets are managed by workplace safety codes and commonly include: training in

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handling hazardous materials; confined space training; minimizing direct contact with fecal matter; wearing protective equipment; sanitation; and vaccination against blood borne diseases (Land, 1995).

Onsite discharge of liquid effluent from composting toilets is managed similarly to septic tank effluent in order to prevent contamination of surface water or ground water by nutrients or pathogens (WSDOH, 2007). Septic field guidelines and regulations are commonly enforced at the local authority level requiring construction of an engineer approved septic field (WSDOH, 2007). Assuming proper construction, soil conditions, and separation distances to water, the impacts of leachate are low (Moore, 2010).

Onsite discharge of solid end-product from composting toilets is regulated as per larger biosolids composting facilities under federal (EPA, 2003), state (e.g. WSDOH, 2007), and local codes (e.g. Snohomish Health District, 2004) in the USA and under provincial codes in Canada (e.g. BC 198/2007 and Alberta Regulation 192/1996) with federal guidelines (CCME, 2005). Composting biosolids for reuse in a public park setting requires time–temperature monitoring and regular testing to ensure conformity and ensure pathogens are destroyed, nutrients matured, and material stabilized (Haug, 1993; AR A.R, 192/1996, BC REG 198/2007). Most regulations stipulate compost must attain temperatures above 55 °C for >3 days (CCME, 2005). Pathogen must be reduced to <1000 MPN/g fecal coliforms (dry solids) must be recorded in finished material indicative of a 4log reduction (99.99%) in the wide range of more virulent pathogens found in human biosolids (de Bertoldi et al., 1983; Haug, 1993; Guardabassi et al., 2003). Ideally, a complete pathogen assay would be conducted, especially when employing a non-standard process, where a passing grade would find no infective viruses (<0.25 PFU/g ds), no viable *Ascaris* spp. (<0.5viable ova/g ds), median of all samples <1 MPN/g ds for *Salmonella*, and median of all samples <10 MPN fecal coliform/g ds, not more than 20% > 1000 MPN/g ds, and none >10,000 MPN/g (Haug, 1993). Testing of this intensity would determine the actual safety of compost toilet end-product, but is not realistic at the scale of these small public composting toilets due to considerable costs necessary for statistical certainty and to cover the heterogeneity in the pile.

NSF/ANSI Standard 41 for Non-liquid Saturated Treatment Systems is one of the only certification standards in North America that directly addresses the biological treatment of waste in public waterless composting toilets (NSF/ANSI, 2011). The standard's purpose is to establish minimum materials, design, and construction, and performance testing of waterless storage/treatment devices and is intended to protect public health and the environment (NSF/ANSI, 2011). Testing is conducted one time on a new system installed at NSF/ANSI headquarters and once on three mature in-field systems. It addresses maintenance hazards by mandating that the design must not require the operator to ever enter into the chamber for maintenance. Addressing the risk of pollution associated with ongoing liquid leachate, five samples of leachate from each system must no have foul odor and <200 MPN/100 ml fecal coliform. Solid end-products from five samples are also tested in order to determine whether units are capable of producing 'safe' material. These limits are: TS% > 35; fecal coliforms <200 MPN/g; and no objectionable odor immediately following removal. No references are provided explaining how the criteria were established or what relation exists between the standards and pathogens of greater concern. Despite testing and certifying end-product, the standard states that it provides no guidance on end-product management and fails to reference national, state, provincial, or local codes governing biosolid reuse (NSF/ANSI, 2011).

In addition to meeting the above regulations and NSF/ANSI Standard 41 criteria, compost by definition should have high quality soil amendment properties, which includes being stable, mature, of balanced pH, free of foreign objects and heavy metals (CCME, 2005; Wichuk and McCartney, 2010).

There are two styles of public composting toilet facilities: mixed latrine style composting toilets (MLMC) where feedstock are mixed together to create the proper energy source for microbially driven

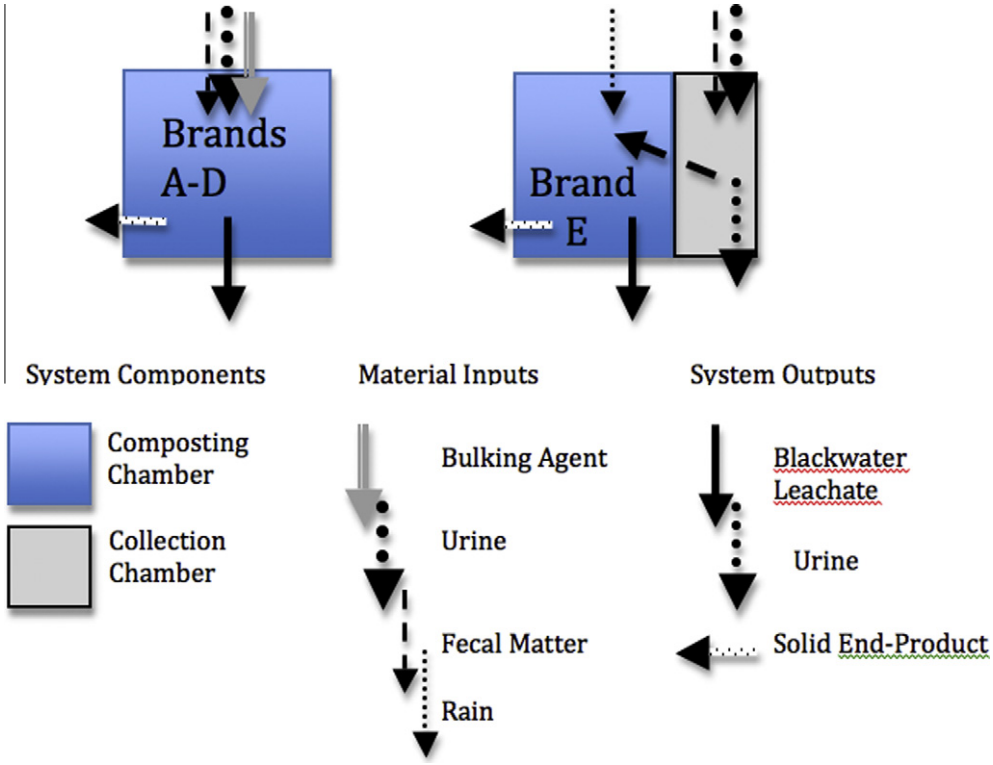

Fig. 1. Mixed latrine style microbial composting (MLMC) toilet and source separating vermicomposting (SSVC) toilet design diagram showing physical chambers, inputs, and solid and liquid material outputs.

aerobic decomposition; and source separating vermicomposting toilets (SSVC) where urine and fecal matter are separated and earthworms are used to degrade fecal matter (Fig. 1). There may be some cross-over between these systems, where earthworms inhabit MLMCs, but in the majority of cases, worms added to MLMCs die rapidly (ON-SITE NewZ, 2000).

There are a number of brands of MLMC available in North America and all are operated in a similar fashion; urine, fecal matter, bulking agent, and toilet paper are added at the toilet hole, liquids leach through and out the bottom or side, and solids are periodically removed to allow room for raw inputs (Fig. 1). White wood shavings, most commonly Pine spp., are used as bulking agent. All require: periodic surface mixing and raking to combine fecal matter with bulking agent; trash removal; and moisture manipulation. All systems are initiated ½–¾ full of bulking agent. Some recommend auxiliary heaters.

MLMCs are designed and operated to enable aerobic decomposition by including: porosity for oxygenation through structurally resistant bulking agent; homogeneity through mixing or raking bulking agent into fecal matter; elevation of C/N ratio from 6 (night soil) to 15–30 (optimal) by addition of carbonaceous bulking agent; and drainage to prevent saturated anaerobic conditions. In addition to decomposition of material, MLMCs also propose to sanitize the pile of harmful pathogens as a result of long storage times and out competition with benign micro-organisms.

The limited body of literature on MLMC, especially field versus laboratory studies, generally does not prove it reliable for decomposition or sanitation of fecal matter. Thermophilic temperatures are seldom if ever attained eliminating this reliable mechanism of pathogen destruction (Redlinger et al., 2001; Holmqvist and Stenstrom, 2002; Jenkins, 2005; Tønner-Klank et al., 2007; Jensen et al., 2009). Jenkins (2005) writes extensively about composting humanure in batches at private residences, yet only notes in passing that most commercial systems for public use fail to attain thermophilic temperatures and are continuous flow design. Should thermophilic temperatures be attained at any point during the year, raw leachate contamination into finished material, a result of the design, could negate any sanitation achieved (Fig. 1). Storage alone is unlikely to be a reliable pathogen destruction mechanism; short-lived pathogens such as fecal coliforms may diminish, but more resistant pathogens such as viruses (Rota virus, Hepatitis A virus) and hookworms can survive multiple years (Gray et al., 1993; Ramos et al., 2000; Guardabassi et al., 2003; Tønner-Klank et al., 2007). Redlinger et al. (2001) found desiccation to be a more effective than composting in pathogen destruction where less than 36% of toilets studied reduced fecal coliform to <1000 MPN/g over a six month period. However, despite efforts to provide drainage, saturation and foul smells consistently plague both public and private MLMCs (Matthews, 2000; Jönsson and Vinnerås, 2007). Despite efforts to increase C/N ratios, the actual carbon available at low temperatures to microbes may be much less than the value reported by loss of ignition (LOI) methods (Kayhanian and Tchabanoglous, 1992), which may lead to high free ammonia concentrations and negative impacts on nitrification (Hill, unpublished). MLMCs were not expected to produce high quality compost, nor adequate or consistent sanitation.

For the reasons above, alternatives to MLMCs are needed, such as source-separated vermi-composting (SSVC), which are commercially available in Europe. Urine and fecal matter, added at the toilet hole are separated from each other either by means of surface tension off the inside of the toilet riser to a gutter or by drainage away from fecal matter off an inclined foot operated treadmill. We visited only the latter in this study. The accumulated solids are periodically shoveled to a finishing pile where earthworms, cultured in matured compost, convert the fecal matter and toilet paper into vermicompost. Moisture is conserved with impermeable pile coverings and/or delivery of rain-water captured on the roof. Process maintenance is minimal as worms are relied upon to mix, aerate, homogenize, and sanitize the excrement.

Invertebrate driven decomposition as an engineered waste treatment process is gaining popularity in developing countries due to its low-tech nature and high quality end-product (Davison et al., 2006; Kumar and Shweta, 2011). Environmental conditions appropriate for vermicomposting, such as ambient temperatures (5–29 °C) and high moisture content (60–75%) are easily maintained at remote or decentralized sites (Sinha et al., 2009). Worms can survive near zero temperatures, their cocoons can survive freezing temperatures, and viable populations have been maintained as high as 2400 m (Hill, unpublshed; Neau, personal communications January 2012). Source separated human waste (Yadav et al., 2010), human biosolids (Eastman et al., 2001), and sewage sludge (Dominguez et al., 2000), all viable feedstocks, have been transformed into vermicompost meeting standards for compost stability and maturity. The majority of research supports the ability of vermicomposting to reliably and greatly reduce pathogens from contaminated feedstock. Yadav et al. (2010) and Brahambhatt (2006) documented total coliform elimination (>8log reduction) in large 60 kg batch tests. Kumar and Shweta (2011) document complete removal of *Salmonella*, *Shigella*, *Escherichia* and *Flexibacter* spp. in an analysis pre, mid, and post worm gut. Eastman et al. (2001) documented more rapid and more complete pathogen destruction (bacteria, virus, and helminth) than thermophilic composting of the same feedstocks using high densities of earthworms. Intestine action, secretion of coelomic fluids, selective grazing, and alteration of microbial community composition, were all cited as important in pathogen destruction (Sinha et al., 2009; Kumar and Shweta, 2011).

In a review of pathogen destruction through vermicomposting, Edwards and Subler (2011) note one study by Haimi and Huhta (1987) in which fecal *Streptococci* spp. increased after vermicomposting, which was one of the only papers found doubting the viability of vermicomposting in complete pathogen destruction given suitable conditions and time. It is hypothesized that SSVC toilets will be more reliable and complete in the destruction of pathogens and production of high quality end-product than MLMC toilets.

Despite the dearth of data on the actual performance of composting toilets in the field, they continue to be used and actively marketed with promises of achieving waste reduction and sanitation goals. This study is the first thorough assessment of the performance of existing public composting toilets at several different sites in the Pacific North West of North America in terms of their operating and management costs, performance with respect to mass and pathogen reduction and the risk that they pose to users, operators and the environment. They were compared with the alternative SSVC adopted at sites in Europe by performing identical measurements. The results strongly show that MLMC is not effective at reducing pathogens as measured by *Escherichia coli* levels nor at reducing contaminated mass (percent volatile solids (%VS)) in contrast to SSVC, in which the end-product was stable, mature and had low *E. coli* numbers.

2. Materials and methods

2.1. Sites

Agencies operating public composting toilets in Western Canada, Pacific Northwest USA and Western Europe were contacted requesting permission to extract samples of end-product for analysis. All those granting permission, and where travel expenses were minimal or covered by the agency or a supporting grant were visited. Seventeen sites were visited. Eleven sites were designated remote (away from roads and motorized access); five of these remote

sites were in campgrounds, six were at backcountry destinations without overnight facilities, and one was within a heated building. Two sites were found within urban buildings; one heated and one not. The remaining four were at trailhead parking lots.

Sites were found scattered between 50 m and 2200 m elevation. The sites received 360–45,000 uses/toilet/year with a concentration of usage in summer months and minimal usage in the winter months except at the MLMC toilet within the public building where usage was more consistent throughout the year and two SSVCs beside ski lifts at ski resorts. A summary of site characteristics can be found in Table 1.

2.2. Chambers

Four brands of MLMC, two suitable for high use (A and C) and two suitable only for low use (B and D) were found in Western North America. One brand of SSVC was found at the five sites in Europe. All were commercial units, sized to handle estimated use based on manufacturer instruction manuals, site use records, and installed professionally. All brands were found in a range of environmental conditions at various sites (Table 2). Heaters were found at a few of the sites visited and consisted of sheets of clear polymer affixed an exterior wall, which slightly warmed incoming air when the sun was shining on them; these were deemed to have an insignificant effect on the process occurring within the chamber. Due to similarities in process and design MLMCs are grouped together for comparisons with SSVC (Table 3).

Pile temperature was measured in the deposition zone and at the point of sampling with a 10 cm long probe digital thermometer. Toilet usage was estimated from the total number of annual site visitors plus day visitors estimated to use the toilet facilities (reported in use/year/per toilet chamber) provided by site operator. Each overnight visitor was assumed to use the toilet three times, day visitors 0.75 times, and public building occupants twice daily.

Table 1
Site characteristics where public latrine style composting toilets were sampled. Ambient temp. (°C) is the average annual ambient temperature surrounding the compost chamber, obtained from records of the mean annual temperature at the nearest city on record, adjusted by subtracting 1 °C for each 100 m elevation gain. Annual use/chamber is estimated from operator records of site usage where each overnight site visitor is assumed to use toilet facilities three times, each day visitor uses the toilet 0.75 times, and each full time building occupant uses the toilet twice in a day. Estimated material age is based on the date the system was started and the frequency and fraction of end-product removed.

Site	# Of units	Brand	# Of sample events	Elevation	Situation	Ambient temp. (°C)	Use/chamber/year	Started	Sampled	Approx. age of material sampled	Removal fraction and frequency
1	1	A	1	2200	Remote camp	1	1700	1998	2011	>8	¼ Every 2 years
2	1	B	1	50	Urban building	11	548	NA	2011	1	1 Every year
3	2	C	1	100	Urban building	20	10,220	2007	2011	5	1 Every 5 years
4	2	A	3	2100	Remote camp	4	3213	2006	2010, 2011	3–6	¼ Every 2 years
5	2	C	1	900	Parking day-use	0	45,000	2010	2011	1	1 Every year
6	2	A	2	2000	Remote camp	4	2754	2007	2010	2–3	¼ Every 2 years
7	1	C	1	75	Parking day-use	11	20,000	2010	2011	1	TBD
8	1	D	1	550	Remote camp	−2	720	2010	2011	1	½–1 Every year
9	1	A	2	2000	Remote day-use	2	8000	Before 2007	2010, 2011	>3	¼ Infrequent
10	1	A	1	600	Remote day-use	9	3360	2000	2011	>6	¼ Every 2 years
11	1	A	1	2000	Remote camp	1	5000	2009 September	2010	1	¼ Every 2 years
12	1	E	1	563	Parking Day-Use	7	5000	2006 June	2012	5	¾ Every 10–20 years?
13	1	E	1	218	Remote day-use	11	6000	2009 April	2012	3	¾ Every 10–20 years?
14	1	E	1	218	Parking day-use	11	6000	2009 November	2012	2	¾ Every 10–20 years?
15	1	E	1	2160	Remote day-use	−4	5000	2008 October	2012	3	¾ Every 10–20 years?
16	1	E	1	2000	Remote day-use	−4	6000	2009 October	2012	2	¾ Every 10–20 years?
17	1	B	1	2000	Remote camp	20	360	2000	2011	0.5	Every few months

Table 2
Compost toilet brand characteristics. Style refers to system design: PF = plug flow; T = tank; B = batch. Process refers to the mechanism of decomposition and sanitation: MC = microbial process; VC = vermicompost. Size (*l*) refers to the average size of units found at each site. Max rated use (#/toilet/year) refers to the designed max capacity as found in manufacturer reference documentation. O&M refers to the frequency of operational and maintenance tasks as per manufacturer reference documentation.

Brand	# Sites	# Chambers	Style	Process	Size (*l*)	Max rated use (#/toilet/year)	O&M	Bulking agent suggested/use (g)	Leachate contamination of end-product possible?
A	6	8	PF	MC	2500	36,000	Weekly	50	Yes
B	2	2	PF	MC	164	1460	Weekly	40	Yes
C	3	5	PF	MC	4500	40,000	Weekly	24	Yes
D	1	1	T	MC	500	NA	NA	NA	Yes
E	5	5	B	VC	3000	40,000	Annually	None	No

Table 3
Characteristics of raw material, MLMC end-product, and SSVC end-product. Means (and standard deviation). *E. coli* (CFU/g-fecal) is *E. coli* (CFU/g) adjusted to remove dilution effect of bulking agent on MLMC samples based on the estimated fecal: total mass ratio 0.23:1 g fecal origin: gram final dry mass. For sites sampled >1 time, only data from the site-visit with the greatest sample size has been included.

	Brand	*n*	Elev. (m)	Ambient temp. (°C)	Material age (year)	%VS	*E. coli* (CFU/g)	*E. coli* (CFU/g-fecal)	Nitrate (mg/kg ds)	pH	Solvita® ammonia
Raw	A	23	2075	5	<0.5	85 (4)	8545 (2342)	8545 (2342)	286 (1132)	8.1 (0.5)	1.4 (0.7)
MLMC	A, B, C	46	1202	7.5 (7.5)	3.6 (2.8)	82 (13)	19,204 (60,768)	71,128 (225,067)	1303 (429)	8.0 (0.7)	2.6 (1.5)
SSVC	E	15	1031	4.4 (7.4)	3.0 (1.2)	60 (10)	200 (245)	200 (245)	1961 (700)	7.4 (0.3)	4.0 (0)

2.3. Samples

Grab samples were extracted from the compost chamber with a gloved hand from the bottom/oldest sections of the material pile in similar fashion to methods outlined in NSF/ANSI Standard 41 (2011). From the grab-sample, a subsample was scooped with a sterile glass sample jar. At each site reported, two to five samples were extracted from representative sections of the bottom of the pile. Samples were placed into sterile glass jars in a cooler with ice packs for overnight transport by courier to the commercial laboratory for analysis. In the majority of cases the laboratory received the samples within 24–48 h of sampling and a minority within 72 h. Grab samples of raw excrement were extracted from the deposition zone (top) of some toilets in order to establish a baseline of feedstock characteristics. Two chambers were sampled on three separate occasions and a third chamber was sampled on two separate occasions to test the repeatability of the sampling method. Where MLMCs are grouped together and compared to SSVCs, repeat measurements from the same sites were not included. Instead, one sample-visit was chosen to represent the site based on the visit with the largest sample size.

2.4. Biochemical analyses

E. coli is reported as the number of colony forming units (CFUs), as membrane filtration techniques were more economical given our large sample size. Even though there are other species within the fecal coliform group, *E. coli* are commonly used to indicate fecal pathogens (Foppen and Schijuven, 2006). A CFU/g count of *E. coli* will contain an equal or greater number of CFU/g fecal coliforms. Further, CFU values are generally more conservative and less variable than MPN (Gronewold and Wolpert, 2008). Benchmark Laboratories (an ISO 17025 accredited Laboratory in Calgary, Alberta) ran simultaneous tests comparing their CFU/g assay to MPN/g values and found this to be the case in all four samples (data not shown). Dilutions and thorough agitation ensured a homogenous slurry from which the subsample was extracted for plating. Any samples with visible nematodes were sent for analysis. All values are reported as per dry solids (ds) unless specified otherwise.

2.4.1. MLMC samples

Benchmark Laboratories analyzed solid end-product samples for the following parameters (units in brackets) (followed by test procedure): TS(%)(APHA Method 3540B); VS(%)(APHA Method 2540); pH (cold water shake, 1:2, sample:water, followed by measurement with VWR symphony pH probe at 25 °C); *E. coli* (CFU/g ds) (cold water shake extraction followed by USEPA Approved Method 1604, with only *E. coli* reported by membrane filtration using a simultaneous detection technique (MI Medium)); Nitrate (mg/kg ds)(by ion chromatography using APHA Method 4110A),

Product maturity as defined by NH_3 production was measured with the Solvita® ranking method (1–5) using a colorimetry scale read by eye off the chart provided after sample preparation according to the instruction manual: no moisture adjustment, 1–2 h equilibration without lid followed by 4 h at 20-25 °C with lid on. According to the Solvita® manual, at pH 8.0, values of 1 and 5 correspond to >20,000 mg/kg ds and <1000 mg/kg ds ammoniacal-N respectively.

2.4.2. SSVC samples

Laboratoire Departmental D'Analyses de la Drome Laboratories in Valence, France, with accreditation by Cofrac no. 1-0852, 1-1873, analyzed solid end-product samples for the following parameters (units in brackets)(followed by test procedure): TS(%)(NF EN 12880): VS(%)(NF EN 12879); pH (NF T90-008 avr 53), total ammonium (mg/kg ds)(NF EN 25663), nitrate (mg/kg ds)(NF EN ISO 10304-2), and total ammonium (mg/kg ds)(NF EN 25663). *E. coli* (CFU/g ds)(NF V 08-053 (11/02)) was sub contracted to Laboratoire Departmental d'Analyses et de Recherche, also having Cofrac no. accreditation 1–0551 and scientific validatin by Sylvie LECOCQ.

Solvita maturity rank was estimated by converting total ammonium to free ammonia with the temperature and pH of the sample and Emmerson et al.'s (1975) table of free ammonia percent, and then calculating the Solvita class using a regression equation (see Supplemental materials).

Worm counts were made from six 100–200 g samples of mature vermicompost. Worm density was determined by dividing worm mass by material mass (g-worm/g-material (wt).

2.4.3. Statistical procedures

The detection limit value was assigned to samples when *E. coli* counts were reported at or below the detection limit. The detection limit value varied between 50 and 100 CFU/g (ds). JMP version 8 (SAS 2009) was used to perform analysis of variance (ANOVA) and non-parametric Wilcoxon–Kruskal Wallis tests. Parametric tests were used when all assumptions were met (normality, homogenous variances, linearity) and non-parametric methods were used when assumptions were not met. Any other transformations are described within the text.

3. Results and discussion

A framework emerged through discussion with senior park managers and operators, which was used to evaluate MLMC and SSVC performance as waste management systems. Remote site waste management systems need to address four criteria before on-site land application of end-products becomes a realistic goal:

- Centralized collection
- Low operation and maintenance (O&M) costs
- Low risk to site operators, site visitors, local environment
- Mass reduction

Centralized collection brings fecal matter to one controlled location. This can be accomplished by a standard toilet building or a collection bin for personal pack-out containers. Operational costs vary by site and are impacted by many factors making comparisons between systems difficult. Human waste is not valuable until it can be proven otherwise and thus should be minimized to reduce costs, handling risks, and potential disposal costs. In a composting toilet mass can be lost by degrading the organic fraction of solid material which can be evaluated through reduction of volatile solids percent (%VS).

We evaluated O&M costs, exposure risk, and mass reduction by creating a simple model based on an average remote site experiencing 5000 uses/toilet/year, located 0.5 h by car and 0.75 h walk away from agency headquarters, labor costs of $100/h, $50/h for travel expenses, and compost toilet specific input parameters sourced from manufacturer literature and from our results here (see Supplemental material for details).

3.1. Centralized collection

All toilets visited were clearly labeled and recognizable as toilets, meeting the first objective of remote site waste management.

3.2. O&M costs

According to instruction manuals MLMCs require much more operation and maintenance than SSVCs. Field operators generally

followed instruction manuals provided with units. In general MLMCs require daily, weekly, or monthly O&M and SSVCs require annual O&M. The model calculations showed that it would cost $2665/year to service such a site with a MLMC ($0.38/use) and a mere $273/year to service it with a SSVC ($0.02/use). Should the site double in annual use to 10,000, the cost for MLMC O&M would rise to $4583 but would not change for SSVC as the cost per use is essentially constant up to 40,000 users/year (Neau, personal communications January 2012). These predicted costs are the same order of magnitude as the actual ones. For example the company supplying the SSVC sells annual service agreements, after the initial 5 year service inclusion expires, for 500 € per year (Neau, personal communications January 2012). One site serviced by a MLMC, which experienced less than 5000 uses/toilet incurred 10 O&M visits per year, 1 h travel/visit (50/50 toilets/other), 1 h/toilet/visit (50/50 cleaning/operations), 3 h bulking material supply and acquisition/year, 8 h disposal/year (every 2–3 year), plus $100 in fuel totaling $1800 before material disposal costs (Cieslak, personal communications September 2010).

3.3. Risk

3.3.1. MLMC pathogen reduction mechanism

Temperatures >35 °C were not recorded either at the top of the pile (most oxygen) or at the bottom of the pile at any of the sites visited. Composting regulations stipulate that temperatures >55 °C be attained for consistent periods of times (3 days–3 weeks) to ensure adequate pathogen destruction (Haug, 1993; CCME, 2005; BC, 198/2007). Toilets were sampled during periods of use (spring-fall for backcountry sites and winter for urban sites and ski hills) and it can be reasonably assumed that thermophilic conditions do not exist, or rarely exist, in any composting toilet sampled. All literature on the topic of compost toilets concurs that thermophilic conditions do not develop in these small, field scale, decentralized systems (Redlinger et al., 2001; Holmqvist and Stenstrom, 2002; Guardabassi et al., 2003; Zavala et al., 2004; Zavala and Funamizu, 2005; Jensen et al., 2009; Tønner-Klank et al., 2007). Niwagaba et al. (2009) was only able to attain thermophilic temperatures in insulated, bench-scale reactors with urine diverted fecal matter mixed with food waste; without foodwaste or insulation insufficient temperatures allowed *E. coli* and *Enterococcus* spp. to increase during the trial.

Even should thermophilic conditions develop for short periods of time, the toilet design confounds any sanitation as leachate can percolate from the above fresh fecal matter into the more mature material and re-contaminate it.

Storage time on its own is not an approved or reliable pathogen reduction mechanism (Vinnerås et al., 2003). Even in desiccating toilets where ash was used to elevate pH to >9, and *E. coli* counts were reduced $5\log_{10}$ units in one year, no reduction in helminth ova or *Clostridium perfringens* were found (Sherpa et al., 2009).

As no proven pathogen reduction mechanism appears to be present in MLMC systems, piles contaminated with resistant pathogens such as helminth ova, would contain this pathogen in end-product and potentially in leachate. *Rhabditis* spp. and *Diploscapter* spp., parasitic, free-living nematodes were found together at Site 2, and the latter on its own, along with other natural soil nematodes, was found in an old dump pile adjacent to Site 1. *E. coli* in end-product are included in Section 3.5 onsite disposal.

3.3.2. SSVC pathogen reduction mechanism

The average worm density was 0.03 ± 0.04 g-worm/g-material (0.024 ± 0.030 g/ml). This density is similar to the maximum density obtained in experimental trials with sewage by Benitez et al. (1999) (0.05 g-worm/g-feedstock), which produced mature and stable vermicompost in nine weeks, and Kumar and Shweta who eliminated all bacterial pathogens evaluated in 8 weeks with a starting density of 0.005 g-worm/g-feedstock (assuming the average mature worm was 0.5 g (Yadav et al., 2010)). In order for earthworms to predate upon pathogens, consume fecal matter and indirectly destroy pathogens, and facilitate further pathogen reduction by altering microbial community composition, they must have a moist, neutral, and low ammonia environment (Sinha et al., 2009; Eastman and Subler, 2011). The average TS(%) was 27 ± 10, within the range of optimal moisture (Sinha et al., 2009). The vermicompost was of neutral pH and the ammonia content was low (Table 3). The worm density found in these samples confirms that healthy populations of worms had established, and were likely responsible for the considerable material degradation (section 3.4) and pathogen reduction (section 3.5) found here.

3.3.3. Risk exposure events

Exposure events were modeled at a 5000 user/toilet/year site in similar fashion to the cost analysis; each O&M procedure (as suggested by instruction manuals) which placed the operator in close proximity or contact with raw or finished end-product was counted as an exposure event and during constant direct exposure (bi-annual shoveling) one exposure was allocated each hour. MLMCs averaged 33 exposure events per year. SSVSs averaged 2.

Due to what appears to be adequate worm density and environmental conditions for pathogen destruction, SSVSs are likely to create less O&M risk than MLMCs, which appear to lack a proven pathogen reduction mechanism and incur an >10 times the number of annual exposure events during O&M visits. Operators of composting toilets, and especially MLMCs should minimize the exposure and consequences of O&M risks by wearing proper personal protective equipment, obtaining training on handling hazardous materials, working in confined spaces, and obtain blood borne pathogen vaccinations as outlined in Land (1995).

3.4. Mass reduction

Due to limited record keeping, difficulty collecting data on feedstock additions, leachate drainage, CO_2 respired, and end-product removal, mass reduction was estimated through the reduction of %VS, as decomposition of organic matter will reduce the organic fraction leaving behind higher ash content.%VS from SSVC end-products (60 ± 10%) was significantly lower compared to MLMC's (82 ± 13%) ($p < 0.0001$). The average and standard deviation from raw faeces samples in the deposition zone was 85 ± 4% suggesting that minimal decomposition takes place once fecal matter is buried under fresh matter in MLMC.

Adding the %VS reduction to another simple model based on the same 5000 use/toilet/year site, the required bulking agent additions as per the instruction manuals, an estimated ratio of feces:urine, average fecal deposit mass, and urine dry solids content (minimal), it was estimated that the average MLMC increased the total dry weight of fecal-contaminated end-product by 274% compared to original fecal dry weight. This was due to the addition of almost 4× the mass of bulking agent as compared with fecal matter and the minimal reduction in volatile solids (Table 3). This bulking also will act to dilute the bacterial or other pathogen indicators, which are measured per gram total end-product. This bulking agent holds considerable water content, the average TS% being 25%, the other 75% being absorbed urine, further adding to total wet mass of end-product that must be periodically removed and disposed of.

SSVCs decreased fecal matter feedstock to 41% of the original dry weight. SSVC average end-product TS% is similar to raw feedstock (28 ± 11%, 25 ± 7%); this high moisture content is necessary for worm survival. This high water content is maintained despite

leachate losses and water lost through cellular respiration with rain-water.

3.5. Onsite disposal

As discussed earlier, thermophilic temperatures were not attained in any cases, nor were they routinely measured by public agencies in any of the MLMC units. Following regulations governing discharge of human waste in British Columbia, Alberta, and the USA, this material should not be applied to public land, and should instead be sent to an approved biosolids treatment facility (BC REG 198/2007, AB AR 192/1996, WSDOH, 2007). Common misinterpretation of these standards is made when a passing grade is assumed by fecal coliforms count alone (<1000 MPN/g); however, this index is only relevant when thermophilic composting has been conducted and documented. Vermicomposting does not occur under thermophilic temperatures, but perhaps due to its recent emergence as a waste treatment alternative, approved process conditions have not yet been developed for vermicomposting making legal land-application of vermicompost challenging. Industrial vermicomposting operations meet regulations by pre-composting vermicompost feedstock thermophilically (Paul, personal communications July 2011).

Full compliance with regulations at all sites visited would involve extracting material for off-site treatment. Given the stringent provincial and federal regulations governing onsite disposal of sewage/biosolids, the role of NSF/ANSI Standard 41 in assessing toilet capable of producing safe end-product is not clear. This is

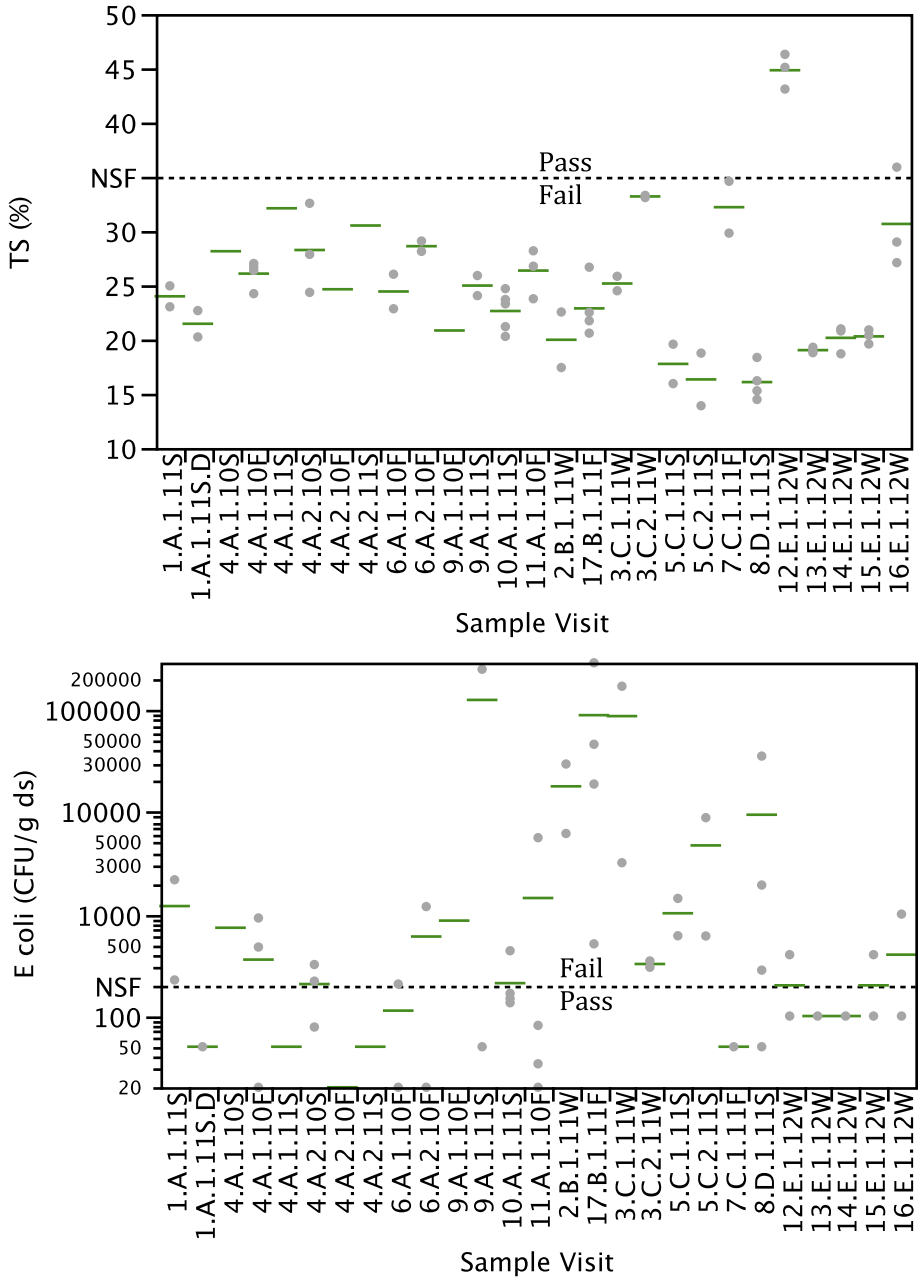

Fig. 2. Performance of composting toilets with solid end-product material grouped in site-sample-visits (Site.Brand.Chamber.Year.Season) as compared with NSF/ANSI Standard 41 TS% and *E. coli* (CFU/g) as a subset of fecal coliforms. D marks samples taken from old end-product dump piles. All data points per site-sample-visit plotted with site-sample-visit mean lines.

exacerbated by the standard's comparatively weak set of analytical methods required to achieve a passing grade in solid or liquid end-product quality (fecal coliforms, total solids, smell) and no recommendations for ongoing analysis. Fecal coliforms are one of the weakest pathogen indicators, having minimal adaptations, unlike protozoan cysts or helminth ova, for long-term survival outside of host organisms (Haug, 1993; Sherpa et al., 2009). Furthermore, the standard appears to provide the purchaser/user an indication of material safety, which according to some manufacturers means end-product is suitable for reuse as soil amendment in residential gardening, yet the standard states that end-product management methods are not addressed by the standard. Based on what is know about composting toilet feedstocks, lack of thermophilic process, and NSF/ANSI Standard 41 test methods, it was predicted that end-product from MLMCs would contain highly variable fecal coliform counts and low total solids due to a high fraction of urine soaked bulking agent.

Fig. 2 confirms this prediction; all MLMC site visits contained samples which failed due to high moisture content, high *E. coli* (fecal coliform) counts, or both. There was no significant difference between *E. coli* counts in MLMC end-product and raw material ($p = 0.42$) (Table 3). High *E. coli* counts on their own are concerning, especially should they contain pathogenic strains such as 0157:H7, but of greater concern, these results suggest inadequate conditions exist to destroy more resistant, virulent and damaging pathogens such as hookworms as demonstrated by Sherpa et al. (2009). Failure to attain proper moisture content for aerobic decomposition plagues MLMCs (Matthews, 2000; Jönsson and Vinnerås, 2007). Desiccating environments are more effective at reducing fecal coliform populations in composting toilets (Redlinger et al., 2001). By diverting urine away from the pile aeration could be improved and possibly lower lower fecal coliform indicators through desiccation. However, this change alone would be unlikely to create safe end-product, as desiccation is not an approved process under provincial or federal regulations in Canada and the USA; protozoa, helminth ova, and viruses can survive desiccating environments (Haug, 1993), especially where material is heterogeneous and contains fecal deposits (Gray et al., 1993). Sherpa et al. (2009) found these exact results, as they show one year of storage in urine-diverting dehydrating toilets achieved significant reduction in *E. coli* and *Enterococci* spp. but failed to induce any reduction in prevalence or abundance in hookworms, tapeworms, or roundworms (Sherpa et al., 2009). In a desiccating environment fecal deposits form a crust within which the moisture content remains higher and may prolong survival (Hill, unpublished). The total failure of all MLMCs in relation to NSF/ANSI Standard 41 and an unclear overlap of the standard in relation to provincial and federal regulations may indicate the need for an overhaul of Standard 41, especially in relation to testing and accreditation of end-product in relation to performance, safety, and regulatory standards.

SSVCs have consistently and significantly lower *E. coli* than MLMCs ($p < 0.0001$); Fig. 3A displays *E. coli* counts (CFU/g-fecal), adjusted to eliminate the diluting effect of 25–50 g bulking agent added every MLMCs use and 2.7:10 fecal:urine usage ratio. This study is one of the first to document SSVCs; as such there is little literature to compare this result to. The NSF/ANSI Standard 41 moisture content limit does not apply to SSVC, which require near-saturated conditions (Sinha et al., 2009). These results, especially in comparison with the data from MLMCs, indicate that vermicomposting human waste may be a reliable process for pathogen destruction. An in-depth analysis of bacterial pathogens and bacteriophages was conducted on the end-product from SSVCs, and will provide further insight (Lalander et al., unpublished).

Should end-products meet regulated standards, either through thermophilic temperature attainment or by inclusion of vermicomposting as an approved process, other aspects of quality should also be achieved including neutral pH, high nitrate, and low ammonia (Haug, 1993; Wichuk and McCartney, 2010). pH is significantly lower, more neutral, and less variable in SSVC end-product ($p = 0.0047$, Fig. 3B). Despite greater annual additions of nitrogen in urine added to MLMCs, total nitrate in the end-product was not significantly different from SSVCs as determined with parametric statistics ($p = 0.42$) (Fig. 3C). This unexpected result may have been caused by an inhibition of nitrification in MLMCs due to a significantly higher ammonia concentration, likely the result of urea hydrolysis, as shown by Solvita® free ammonia value of 2.6 ± 1.5, classifying end-product as phototoxic and immature, which corresponds to a concentration of 4000–10,000 mg/kg (ds) (Woods End, 2000) (Fig. 3D). Nitrifying bacteria are sensitive to high free ammonia concentrations but no composting toilets studies have evaluated the level at which toxicity occurs or addressed the impacts of high urine:fecal ratio on nitrogen biochemistry.

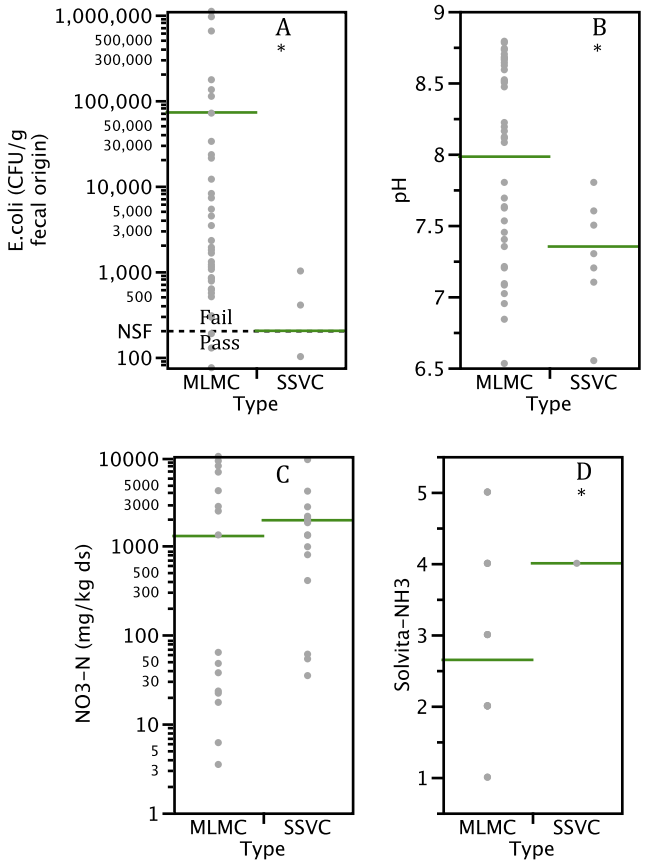

Fig. 3. Comparison of average end-product quality between mixed latrine style microbial composting (MLMC) toilet and source separating vermicomposting (SSVC) in *E. coli* (CFU/g(fecal origin)), pH, Solvita® ammonia, and nitrate (mg/kg ds). All data points per site-sample-visit plotted with site-sample-visit mean lines. Significant differences marked with a ∗.

SSVCs are built to hold 10–20 years of material before extraction of material is necessary. The average age of material sampled was 3 years old but some samples may have been contaminated by material 1–2 year old shoveled onto or near to oldest material. It is expected that as material ages indicators of maturity (and stability) will improve, especially if more care is taken to prevent the mixing of material each year.

4. Conclusion

SSVC toilets have low annual O&M costs, employ a proven pathogen reduction mechanism and show consistently low *E. coli*

counts in end-product, require minimal operational hazards, minimize fecal contaminated leachate, require no bulking agent, reduce end-products to 41% of excrement feedstock dry mass and produce a pH neutral, mature end-product having low free-ammonia and abundant nitrate. MLMCs have 10 times higher O&M costs, employ no proven pathogen reduction mechanism resulting in high and highly variable *E. coli* counts, produce >10 times more operator exposure events, require bulking agent, increase contaminated end-product mass 274%, and fail to produce stable or mature end-product. MLMC end-product from all the sites studied is not suitable for discharge into public park environments. SSVCs outperform MLMCs in relation to the fundamental objectives of remote site waste management, except in the provision of a centralized facility, which was accomplished adequately by both designs. Where worms are present in SSVCs in sufficient density throughout the year, long storage times and adequate separation new and old material should allow for a high degree of stabilization, maturation, and pathogen destruction. Nevertheless, disposal must be conducted according to relevant regulations and vermicomposting is not (yet) an approved method in most locations.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.wasman.2012.04.023.

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