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Production of recycled manure solids used as bedding for dairy cows in Canada: analysis of solid-liquid separation and composting methods

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Abstract. *Increased costs and reduced availability of common bedding materials have prompted Canadian dairy producers to search for alternatives such as recycled manure solids (RMS). Because of the perception that RMS have high bacterial counts, however, the dairy industry is skeptical about using RMS successfully, especially in a wetter, cooler area like Canada. At this point, it is hard for dairy producers to identify the best RMS production options. Therefore, the present study aimed to compare three solid-liquid manure separators (decanter centrifuge, roller press, and screw press) and four composting techniques (static or turned windrow and drum composter for 24 or 72 h) based on their performances and their impacts on RMS and air quality. In order to compare separators, the quantity of processed manure and the volume of the resulting solid fraction were measured, power consumption of separators was recorded, and samples of each constituent were collected for physical, chemical, and bacteriological analyses. When evaluating composting approaches, the RMS temperature and quality and the air quality (gas emissions and airborne microorganisms) were monitored, whereas 2 m^3 of RMS per treatment were distributed into twelve independent bench-scale rooms in which was installed a polyethylene pipe to contain RMS during 10 d. The results suggested that Canadian dairy farmers should be oriented towards press separation and drum composting for 24 h to produce high-quality RMS. Presses are advantageous in terms of cost and RMS quality, and the use of a drum composter for 24 h allowed a maximum reduction of main bacterial species.*

Keywords. *Alternative bedding, Bacterial counts, Cattle slurry, Composted material, Gaseous emissions, Physico-chemical properties, Press, Rotating vessel, Separated manure, Windrow.*

Introduction

Approaches to separate solids from the liquid of cow manure have been known for a while and the use of the dewatered material as bedding is increasing in popularity on dairy farms (Garcia and Diaz-Royón, 2014; House, 2016; Leach et al., 2015). Following solid-liquid separation, fresh recycled manure solids (RMS) may be used directly in stalls without treatment or subjected to a composting procedure before being placed under the cows (Cole, 2015; Harrison et al., 2008; Husfeldt et al., 2012). However, laboratory studies reported that RMS have a greater ability to promote the growth of environmental bacteria than other bedding products (Godden et al., 2008; Zehner et al., 1986). As a result, dairy stakeholders are skeptical about using RMS successfully as bedding in the stalls (Harrison et al., 2008; Husfeldt et al., 2012; Meyer et al., 2007), especially in wet and cold areas such as Canada (Leach et al., 2015). Moreover, reliable research data on the use of RMS as bedding material for dairy cows, including methods of obtaining RMS, are scarce (Endres, 2013; Gooch et al., 2005; Leach et al., 2015).

Solid-liquid separation of dairy manure can be accomplished by a number of methods including stationary, vibrating, or rotating screens, screw or roller presses, and centrifuges (Ford and Fleming, 2002; Katers et al., 2003; Zhang and Westerman, 1997). Screens are the most extensively tested separators, but they generally work better with manure containing a low dry matter (DM) level. In contrast, presses and centrifuges operate well when manure contains a high amount of DM and can reach higher separation efficiencies and produce drier solids than screen separators (Christensen et al., 2013; Zhang and Westerman, 1997). Fresh RMS can be composted in static piles for 3 to 10 d (Harrison et al., 2008), in windrows turned every few days for two weeks (Timms, 2008), or through mechanical drum-composting for 18 to 72 h at approximately 65°C (Harrison et al., 2008; House, 2016; Husfeldt et al., 2012). Further decomposition in heaps is often necessary for drum-composted matter to reduce phytotoxicity (Heinonen-Tanski et al., 2006; Rynk et al., 1992). Reports comparing the aforementioned approaches for the production of RMS under a humid continental climate using controlled experimental conditions are limited (Cole, 2015).

At this time, it is therefore difficult for Canadian dairy producers to identify the best equipment to obtain RMS, considering that separators and composting methods have never been tested and compared using the same manure as influent. Therefore, the present study aimed at assessing the performance of three solid-liquid separators (screw press, roller press, and decanter centrifuge) and four composting procedures (static or turned windrow and drum composter for 24 or 72 h) for the production of high quality RMS bedding.

Materials and Methods

Solid-Liquid Separation

Experimental Setup and Design

A 2-week experiment was conducted from May 23 to June 6, 2017, at the Centre de recherche en sciences animales de Deschambault (CRSAD), QC, Canada. Three separators were tested. The first separator was a decanter centrifuge (B/DF 300 model, Bargam, Cingoly, Italy; approximate original cost = $145,000) consisting of a drum rotating at high speed so that the centrifugal force causes product separation into a solid part and a liquid part. The second separator was a roller press (XPress model, GEA Farm Technologies, Drummondville, QC, Canada; approximate original cost = $75,000) consisting of an inlet hopper followed by two pairs of rollers in a cascading configuration. The third separator was a screw press (FAN model PSS 2-520, Bauer Group, Michigan City, IN, USA; approximate original cost = $75,000) consisting of an electrical motor that drives a stainless steel auger.

The experiment mainly took place under a semi-circular, membrane-covered building where the screw and roller presses were installed (Figure 1). The decanter centrifuge was placed in a trailer. Between the hoop structure and the centrifuge trailer, a temporary 5.5 m diameter slurry tank was assembled to contain approximately 50 m^3 of fresh manure. A manure agitator (AE-7-1/2-7 model, J. Houle & fils Inc., Drummondville, QC, Canada) was installed on the edge of the tank to stir slurry manure during experiments. A centrifugal pump (HS2037BHF model, Goulds Water Technology, Seneca Falls, NY, USA) was placed at the bottom of the tank to feed each separator. Long 5-cm-diameter pipes provided transport of manure from the pump to the separators and from the separator overflows to the tank. At the exits of the screw and roller presses, the solid effluents dropped onto a belt conveyor before accumulating in a tractor-pulled trailer. For the decanter centrifuge, the solid effluent was removed with a screw auger before falling into the same trailer. Liquid effluent was evacuated from each separator by gravity to a 75-L plastic basin from which it was pumped to six 1,000-L containers on a flat tractor-pulled trailer. A power unit (QAS 150T3 model, Atlas Copco, Rock Hill, SC, USA) consisting of a 120-kW generator delivering 3-phase voltage (600 V) provided electricity to the separators, agitator, pumps, and computers.

At the beginning of each week, the slurry tank was filled with fresh manure coming from the in-barn storage pit of a nearby dairy farm using RMS for 5 yr. During the following days, the three separators were randomly tested with manure of a maximum of 7 d of age. Each experimental test lasted the time necessary for the separator to produce at least 0.5 m^3 of solids (between 15 and 100 min according to the separator capacity).

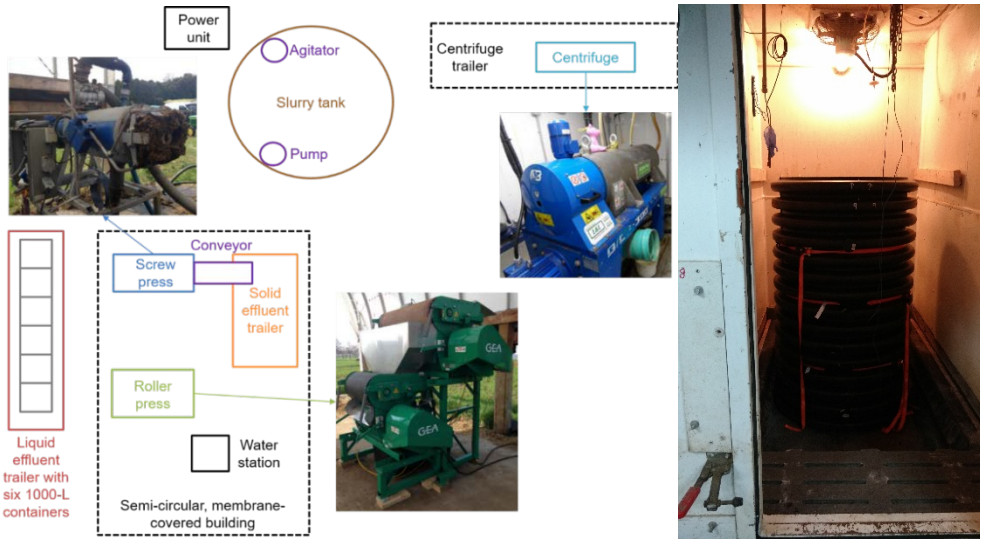

Figure 1. Schematic view of the experimental setup for solid-liquid separation (left) and composting methods (right).

Data Collection, Analytical Procedures, and Calculations

During each experimental test, three 0.5-L samples of fresh RMS were collected at the 5th, 10th, and 15th min, and power consumption of the separator was recorded using split core current transformers (Dent Instruments, Bend, OR, USA) connected to a power submeter (PowerScout 3037 model, Dent Instruments, Bend, OR, USA) linked to a microcomputer (X8 model, Pipo, Shenzhen, China). The solids samples were collected at the end of the conveyor for the screw and roller presses or at the end of the auger screw for the centrifuge. Physico-chemical and bacterial analyses of RMS were performed within 2 weeks and 48 h after sampling, respectively, following the methods described in Table 1.

Table 1. Test methods used for physical, chemical, and bacteriological analysis of fresh recycled manure solids.

Analysis type and property	Method
Physical	
Particle size distribution	Screening through steel sieves with 1 and 4 mm openings
Chemical	
Dry mater	Gravimetric method with oven at 105 °C
Total Kjeldahl Nitrogen	Sulfuric digestion and colorimetric determination by SEAL AA3 AutoAnalyzer
Phosphorus	Sulfur digestion and determination by inductively couples plasma optical emission spectrometry
Bacteriological	
E. coli	Direct plating on 3M Petrifilm *E. coli*/coliforms count plates
Klebsiella spp.	Direct plating on MacConkey no. 3 agar
Enterococcus spp.	Direct plating on m-enterococcus agar
Staphylococcus spp.	Direct plating on Vogel-Johnson agar
Streptococcus spp.	Direct plating on modified Edwards agar

The level of slurry manure in the tank was measured before and after each experiment to determine the total volume of manure processed. Mass flow rate of RMS was determined by subtracting the final weight of the trailer by its tare weight (measured on a 3025MPV scale, Fairbanks, Kansas City, MO, USA) and by dividing the result by the running time of the experiment. Volumetric flow rate of RMS was calculated knowing the density of the constituent through physical analysis.

In order to compare physical, chemical, and bacterial characteristics between separators, concentrations were reported on a DM basis. Bacterial counts were also log-transformed to be expressed in $\log_{10}$ cfu g^{-1} of DM. Energy consumption was determined using the electrical power equation. The separation efficiency, which is the ratio of the total mass recovery of a given component (DM or nutrients) in the solid phase as a proportion of the total input of that component, was calculated according to the method described by Cocolo et al. (2012).

Composting Methods

Experimental Setup and Design

A 2-week experiment was conducted from July 3 to 14, 2017, at the Centre de recherche en sciences animales de Deschambault (CRSAD), QC, Canada in a research facility consisting of twelve independent bench-scale rooms (1.2 m width x 2.4 m length x 2.4 m height) arranged side by side. Each room was equipped with a variable-speed exhaust fan. The incoming air was the same for all the rooms and came from a main duct in which it is preconditioned. An air conditioning unit or a heating device was used, if necessary, to cool or warm the air before entering the rooms. The inside temperature of the rooms was set to 23°C. On the concrete floor of each room, a polyethylene drainage pipe (1.5 m deep and 0.75 m in

diameter) was installed to contain 0.67 m^3 of RMS during 10 d (Figure 1). The experimental setup was used to simulate the middle column of a large compost pile and follow the evolution of RMS through time. One of the four following composting approaches was randomly attributed to each of the twelve rooms:

1. Static windrow (SW) consisting of fresh RMS loaded into the pipe and immobile for 10 d;
2. Turned windrow (TW) consisting of fresh RMS loaded into the pipe and turned every day for 10 d;
3. Drum composter for 24 h (DC24) consisting of fresh RMS loaded in a drum composter for 1 d before being placed into the pipe for 10 d;
4. Drum composter for 72 h (DC72) consisting of fresh RMS loaded in a drum composter for 3 d before being placed into the pipe for 10 d.

On the first day, the slurry tank of the separation experiment was refilled with fresh manure. The slurry manure was then separated using the FAN screw press. Newly separated RMS were loaded in a trailer to transport the material towards the research facility. Approximately 6 m^3 of fresh RMS were produced. One third of the production was used to fill the pipes of the three SW rooms and another 2 m^3 were loaded into the TW pipes. The remaining RMS were loaded in a commercial drum composter (1.2 m in diameter x 3 m length; AGF Brome, Cowansville, QC, Canada). The process lasted 24 h in order to complete the DC24 treatment. On the following day, the drum composter was emptied and the material was loaded into the DC24 pipes. Another 2 m^3 of RMS for the DC72 treatment was produced with the same separation setup. The drum composter was then filled with the fresh material and worked for 72 h. At the end of the processing period, RMS were loaded in the DC72 pipes. Recycled manure solids remain static into the pipes for 10 d for treatments SW, DC24, and DC72. For TW rooms, RMS were turned daily in the morning by discharging manually with a shovel all the content of the pipes and by reloading them by paying attention to invert top and bottom material.

Data Collection and Analytical Procedures

Recycled manure solids were sampled at different occasions during the experiment: after solid-liquid separation (all treatments), after drum-composting (DC24 and DC72 treatments only), and after 5 and 10 d into the pipes (all treatments). Sterile disposable plastic scoops were used to sample randomly each 2 m^3 of produced RMS and each type of drum-composted RMS on day 0, while sampling of RMS on days 5 and 10 for all treatments was done by inserting a core drill into the three fixed sampling ports created on the pipes. Samples of RMS (between 0.5 to 1.0 L) were collected for physico-chemical and bacteriological analyses following the methods presented in Table 1.

In each room, composted RMS temperatures were measured using two type T thermocouples inserted into RMS at different locations (middle of top and bottom half). Ventilation rates were calculated from a 204-mm iris orifice damper (Model 200, Continental Fan Manufacturing Inc., Buffalo, NY, USA) installed in the exhaust duct of each room. Gases from each room were pumped to a mobile laboratory through Teflon tubing. Ammonia (NH_3) was analyzed by a Non-Dispersive Infrared Analyzer (NDIR; Ultramat 6E model, Seimens, Munich, Germany), and greenhouse gases, namely carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), were analyzed by gas chromatography (GC; model 3600, Varian, Walnut Creek, CA, USA). All instruments were connected to a data logger (CR1000 model, Campbell Scientific, Edmonton, AB, Canada) which recorded average values every 15 min.

Airborne microorganisms and dust were sampled in each chamber at 2.5 cm (SW, DC24, and DC72 treatments) or 5.1 cm (TW treatment) above the top of the pipe. A Coriolis-µ Biological Air Sampler (Bertin Corp., Rockville, MD, USA) was used to collect microbes. Airborne dust particles were measured with a DustTrak™ DRX Aerosol Monitor (Model 8534, TSI, St. Paul, MN, USA). Air was sampled in each room at day 0 when loading of the pipes occurred. Air sampling was also done at days 5 and 10 for SW, DC24, and DC72 treatments. For TW treatment, two samples were taken at days 5 and 10: one before and one during RMS turning. Ten-fold serial dilutions of the Coriolis-µ samples were plated on different culture media to determine airborne culturable microbial content. Mesophilic bacteria were counted from plates of Difco™ Tryptic Soy Agar (BD, Sparks, MD, USA) supplemented with 5 µg mL^{-1} amphotericin (Sigma-Aldrich, St-Louis, MO, USA) incubated at 25°C for 3 d. Mesophilic fungi were cultivated at 25°C on Difco™ Rose Bengal Agar (BD) with 50 µg mL^{-1} chloramphenicol (Sigma-Aldrich). Thermotolerant fungi were counted on Difco™ Malt Extract Agar (BD) plates incubated at 52°C. All plates for fungal culture were incubated for 5 d.

Results and Discussion

Solid-Liquid Separation

Table 2 presents the operation performances, main properties of fresh RMS, and separation efficiencies for each separator. The screw press had the greatest measured capacity, separating an average of 20.3 $m^3\ h^{-1}$ of slurry manure (7.0% DM). The treatment capacity reached by the centrifuge (1.5 $m^3\ h^{-1}$) was about 14 times lower than the screw press. The roller press resulted in an intermediate capacity value (9.1 $m^3\ h^{-1}$). The influent flow rate results are consistent with other scientific works (Gooch et al., 2005; Pos et al., 1984; Wu, 2007) using a similar GEA roller press (5.9 to 20.4 $m^3\ h^{-1}$) and FAN screw press (6.6 to 22.0 $m^3\ h^{-1}$) to separate dairy manure. Martin et al. (2006) tested the same centrifuge with pig manure and obtained capacity values ranging between 1.2 and 2.5 $m^3\ h^{-1}$. The present results demonstrated that 10 to 30% of the influent

volume ends up in a solid form, which is very comparable to the reported studies (Gooch et al., 2005; Pos et al., 1984; Wu, 2007). Consistent with the separator treatment capacity, the volumetric flow rates of fresh RMS were different between the separators, ranging from 0.44 to 5.42 m^3 h^{-1}. Table 2 shows that separating manure using centrifugal force is an energy-demanding process, with an average of 4.99 kWh consumed per cubic meter of slurry treated, while both mechanical presses worked properly using less than 0.35 kWh m^{-3}.

Table 2. Separator performances, properties of fresh recycled manure solids (RMS), and separation efficiencies.

	Decanter centrifuge	Roller press	Screw press
Separator performances			
Slurry treatment capacity (m^3 h^{-1})	1.5	9.1	20.3
RMS flow rate (m^3 h^{-1})	0.44	0.87	5.42
Energy consumption (kWh m^{-3})	4.99	0.10	0.35
RMS properties			
Particle size distribution			
< 1 mm (%)	14.9	3.0	1.1
1–4 mm (%)	76.1	32.3	27.5
> 4 mm (%)	6.3	62.1	70.0
Dry matter content (%)	33.7	30.7	25.3
Nitrogen (g kg^{-1} of DM)	18.5	15.6	19.0
Phosphorus (g kg^{-1} of DM)	10.8	3.7	5.2
E. coli (log 10 cfu g^{-1} of DM)	4.59	5.04	4.97
Klebsiella spp. (log 10 cfu g^{-1} of DM)	4.23	4.95	4.92
Enterococcus spp. (log 10 cfu g^{-1} of DM)	6.33	6.62	6.81
Staphylococcus spp. (log 10 cfu g^{-1} of DM)	6.64	6.43	6.92
Streptococcus spp. (log 10 cfu g^{-1} of DM)	6.77	6.71	6.69
Separation efficiencies			
Dry matter (%)	42.5	11.9	35.3
Nitrogen (%)	14.8	3.6	12.6
Phosphorus (%)	47.2	4.6	19.1

The analysis of each RMS particle size category showed a separator effect. The centrifuge produced higher amounts of fine and medium particles than the other separators. In fact, the sieves under 4 mm retained 91.0% of the solid material from the centrifuge, compared to 35.3% and 28.6% for the roller and screw presses. Consequently, both presses generated fresh RMS with coarser particles as the majority of them (> 62%) had a diameter of 4 mm and over.

The screw press produced the wettest RMS with a DM content of 25.3% in average, far from the roller separator and the centrifuge which reached DM concentrations higher than 30.7%. Although screw press results are comparable to values (21.6–25.3%) stated in Møller et al. (2000), Gooch et al. (2005), and Wu (2007) with a similar separator, a higher percentage of DM in the solid material could have been reached with a newer version of the screw press (Valacon-Dairy, 2014). In the literature (Gooch et al., 2005; Møller et al., 2007; Møller et al., 2002), the DM values for the other two separators were comparable to those of the screw press (19.9–23.9%).

The separation mechanism of N and P differed between separators. The roller press seemed to produce N-low RMS. All N results are in accordance with the ranges (7.9–29.6 g kg^{-1} of DM) reported by several studies (Gooch et al., 2005; Møller et al., 2007; Møller et al., 2000; Møller et al., 2002; Pos et al., 1984). These works tended to demonstrate that the centrifuge produced an N-rich liquid manure, while the roller press had much less N in separated fractions. Most of the P with the centrifuge ended in the RMS (10.8 g kg^{-1} of DM), while the solid fraction from both presses only contained 3.7–5.2 g kg^{-1} of DM. In fact, P during roller and screw separation is largely directed to the liquid phase where P levels (> 10.3 g kg^{-1} of DM) are higher than that of the centrifuge (7.4 g kg^{-1} of DM). Literature also suggests that the centrifugal process has the ability to concentrate P in the solid fraction. Møller et al. (2002) and Møller et al. (2007) found 9.0–13.6 g P kg^{-1} of DM in centrifuged RMS, while a group of studies (Gooch et al., 2005; Møller et al., 2000; Møller et al., 2002; Pos et al., 1984; Wu, 2007) obtained 1.8–6.0 g P kg^{-1} of DM in pressurized RMS. These results highlighted that P-based compounds are likely attached to fine particles that are a dominant fraction of RMS produced by a centrifuge.

No separator demonstrated superior efficiency to reduce levels of bacteria in fresh RMS. These observations agree with Liu et al. (2017) who reported negligible changes in *E. coli* counts in RMS sampled after centrifugation. Leach et al. (2015) reported similar *E. coli*, *Klebsiella* spp., and *Streptoccoccus* spp. levels and lower enterococci and *Staphylococcus* spp. counts than in the present study.

The centrifuge recovered in average 42.5% of DM, 14.8% of N, and 47.2% of P in the solid phase. These numbers are about 20 percentage units lower in each category than those reported by Møller et al. (2002) and Møller et al. (2007) who used other European centrifuges to separate dairy manure. The screw press produced RMS with 35.3%, 12.6%, and 19.1% of the total input of DM, N, and P, respectively. These results are more comparable to the literature as the respective separation efficiencies average 40.2%, 13.2%, and 12.2% (Brito et al., 2008; Converse et al., 2000; Gooch et al., 2005;

Møller et al., 2000; Møller et al., 2002; Wu, 2007). As highlighted by Cocolo et al. (2012), the roller press achieved low separation efficiencies, ranging between 3.6% for N to 11.9% for DM. However, Gooch et al. (2005) obtained results near 40% and 18% for DM and N with the same roller separator on a farm.

Composting Methods

Physical, chemical, and bacteriological properties of fresh RMS during the composting experiment were similar between treatments and comparable to results in Table 2 for the screw press. Before being loaded in the tubes, DC24 and DC72 RMS passed through the rotating vessel. While physical and chemical characteristics did not significantly vary, *E. coli* and *Klebsiella* spp. counts observed in drum-composted materials dropped. A 24 h passage through the drum was enough to decrease those pathogens by 74% and 43% (Table 3), respectively. Similar or lesser reductions were observed for the DC72 treatment for both bacteria species. Increases of 41% and 29% in *Staphylococcus* spp. counts were noted for DC24 and DC72 treatments, respectively. DC72 presented better removal efficiencies for *Streptococcus* spp. and *Enterococcus* spp. (16–23%) than DC24 (0–4%).

Table 3. Bacterial counts[a] (log_{10} cfu g^{-1} of DM) in recycled manure solids after drum composting for 24 h (DC24) or 72 h (DC72).

	DC24	DC72
Escherichia coli	1.3 (–74)	1.3 (–73)
Klebsiella spp.	2.6 (–43)	3.5 (–17)
Staphylococcus spp.	8.4 (+41)	7.9 (+29)
Streptococcus spp.	6.0 (0)	4.9 (–23)
Enterococcus spp.	5.9 (–3.2)	5.1 (–16)

[a] Values in parentheses indicate the variation (%) with the initial count before drum-composting.

During the 10-d composting period in pipes, some differences in physico-chemical and bacteriological properties were notable (Table 4). While particles with a diameter less than 1 mm were almost absent in any composted RMS, medium- and large-size particle distribution depended on whether fresh RMS passed into the drum composter or not. Both drum-composted treatments contained a greater proportion of coarse particles compared to SW and TW treatments (72% vs. 44%). Recycled manure solids from SW and TW were mainly composed of medium particles (52%).

Table 4. Properties of composted recycled manure solids (RMS) during a 10-d composting period for each tested approach: static windrow (SW), turned windrow (TW), drum composter for 24 h (DC24), and drum composter for 72 h (DC72).

	SW	TW	DC24	DC72
Particle size distribution				
< 1 mm (%)	1.9	0.8	0.7	0.8
1–4 mm (%)	51.0	53.3	23.1	29.4
> 4 mm (%)	44.6	42.8	74.9	68.6
Dry matter content (%)	25.6	24.8	26.0	27.0
Nitrogen (g kg^{-1} of DM)	21.5	20.3	22.6	21.9
Phosphorus (g kg^{-1} of DM)	6.5	6.1	6.8	6.7

There were also differences in DM content between composting approaches. Drum-composted RMS tended to be drier by 0.4–2.2 percentage units. Moisture reduction through evaporative losses is a key benefit of the composting process (Bernal et al., 2009; Brito et al., 2008). The SW piles also had a greater DM when compared to TW pipes. Similarly, Brito et al. (2008) observed a difference of 2 percentage units after 14 d of composting in static and turned piles with an initial DM content of 24.9%. The TW composting approach in the present study had the lowest N and P concentration.

The 10-d composting experiment in pipes showed that treatment efficiency to reduce bacterial counts was species-dependent (Figure 2). DC72 showed the greatest sanitization effect on enterococci levels, but increased counts of *E. coli*, *Klebsiella* spp., and *Streptococcus* spp. DC72 was the only treatment during which bacterial regrowth was observed during the 10-d period. Composting in a drum for 24 h reduced *E. coli* and *Klebsiella* spp. (Table 3), but concentrations stayed unchanged in the pipes during the 10-d period. No supplemental reduction was observed in DC72 samples. Besides, keeping static piles of drum-composted RMS for 5 d seems to be a better option than 10 d for DC72 since *Klebsiella* spp. and *Streptococcus* spp. counts increased from day 5 to day 10 in DC72 pipes. *Klebsiella* spp. multiplied in all treatments between day 5 and day 10, except in DC24 composted RMS. TW and SW treatments showed similar bacterial reductions.

Time-temperature profiles recorded during the experiment in pipes followed similar patterns to other investigations reporting the composting of dewatered livestock slurries (Brito et al., 2008; Brito et al., 2012; Cáceres et al., 2006). Figure 3 shows the breakdown of the readily available organic matter and N compounds associated with the mesophilic phase generally lasting 1 to 3 d (Bernal et al., 2009), whereas the temperature of all composting piles in both halves increased up to 40°C during the first 48 h. Between days 3 and 10, RMS entered a thermophilic phase (> 40°C), during which microorganisms degraded fats, cellulose, hemicellulose and some lignin (Bernal et al., 2009). In the bottom section of the pipes, the temperature reached similar levels (40–50°C) for all composted RMS. However, in the top section, TW responded differently

compared to the other treatments. SW, DC24, and DC72 top sections reached approximately 60°C and stayed unchanged until the end of the experiment, while the temperature of the TW top section varied between 35°C and 45°C during the last 7 days. Turning RMS daily for TW treatment was potentially too frequent to allow heat to build-up within pile and to create the chimney effect. In addition, it is likely that the turning operation cooled the material. Turning the mix every 3 or 4 d could have been more favorable to achieve higher temperatures (Keener, 2011).

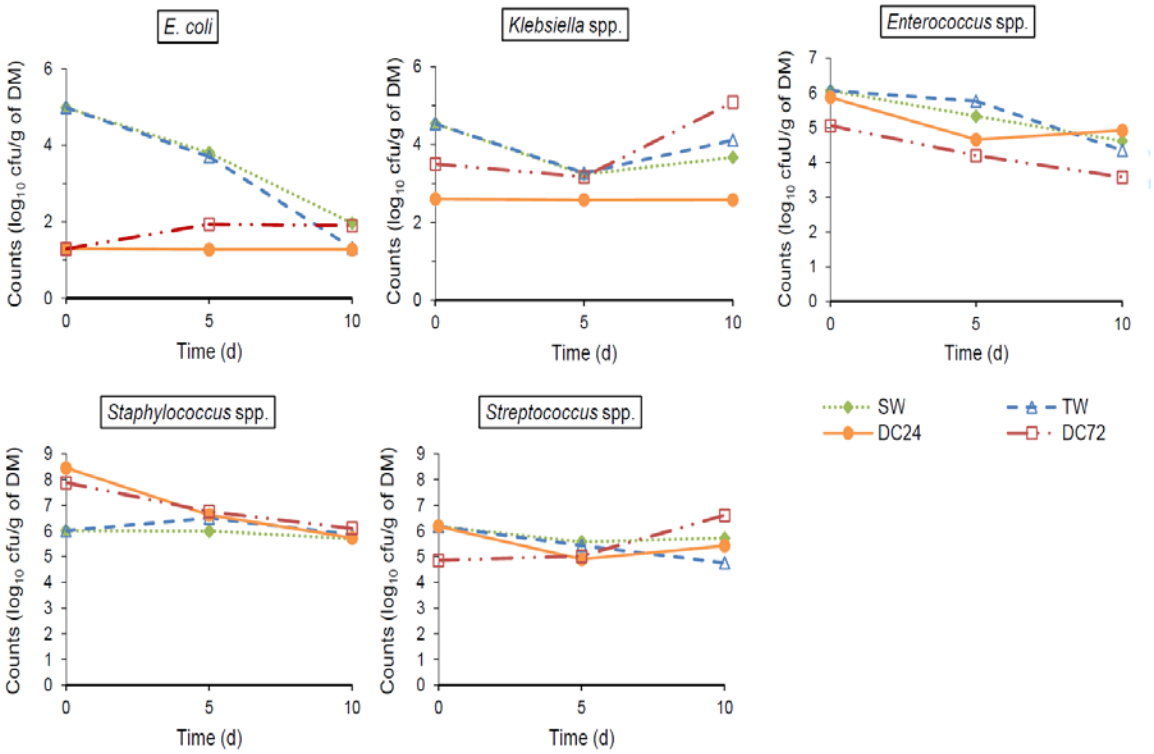

Figure 2. Mean bacterial counts in RMS on days 0, 5, and 10 following different treatments: static windrow (SW), turned windrow (TW), drum composter for 24 h (DC24) or drum composter for 72 h (DC72).

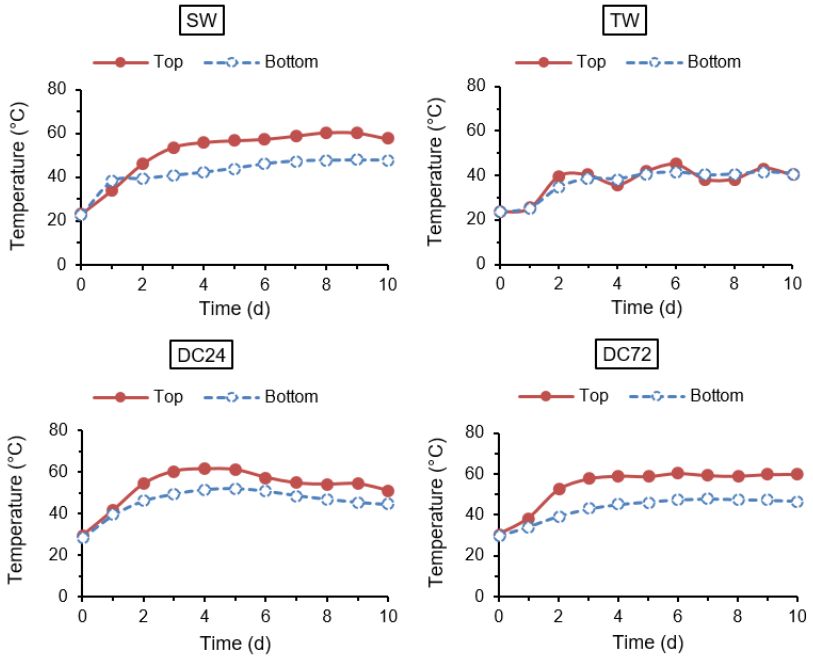

Figure 3. Daily mean temperature over 10 d in top and bottom half of RMS pipes following different treatments: static windrow (SW), turned windrow (TW), drum composter for 24 h (DC24), or drum composter for 72 h (DC72).

Gaseous emissions varied throughout the pile-composting period (Figure 4). For all treatments, NH_3, CO_2, and NO_2 levels peaked in 2 or 3 d, declining gradually afterwards to reach a plateau (1 mg NH_3 min^{-1}, 500 mg CO_2 min^{-1}, and 0.1 mg N_2O min^{-1}). Methane emissions were generally around 10 mg CH_4 min^{-1}. However, some peaks were noted for DC24 (days 2–7), SW (days 7–9), and TW (days 8–10) treatments and could have been the result of momentary favorable anaerobic conditions. In static piles, even with regulated ventilation, preferential flow paths may easily be formed, especially if the moisture, density, and porosity of RMS are not satisfactory. Aerobic conditions may, therefore, predominate in most parts of the piles, while anaerobic pockets are likely to appear and promote the formation of CH_4 (Cole, 2015; Pardo et al., 2015). Dinuccio et al. (2008), Fangueiro et al. (2008), Chen et al. (2015), and Fillingham et al. (2017) similarly investigated gaseous emissions during composting of solid dairy manure in open vessels and static or turned windrows at temperatures over 15°C. When reported per unit of compost volume, present emissions of NH_3 (0.02–2.16 mg min^{-1} m^{-3}), CO_2 (88–1208 mg min^{-1} m^{-3}), CH_4 (1.0–46.7 mg min^{-1} m^{-3}), and N_2O (0.00–0.25 mg min^{-1} m^{-3}) are comparable to the reported gaseous levels of these studies (0.02–4.43 mg NH_3 min^{-1} m^{-3}, 305–2115 mg CO_2 min^{-1} m^{-3}, 1.7–50.3 mg CH_4 min^{-1} m^{-3}, and 0.00–1.13 mg N_2O min^{-1} m^{-3}).

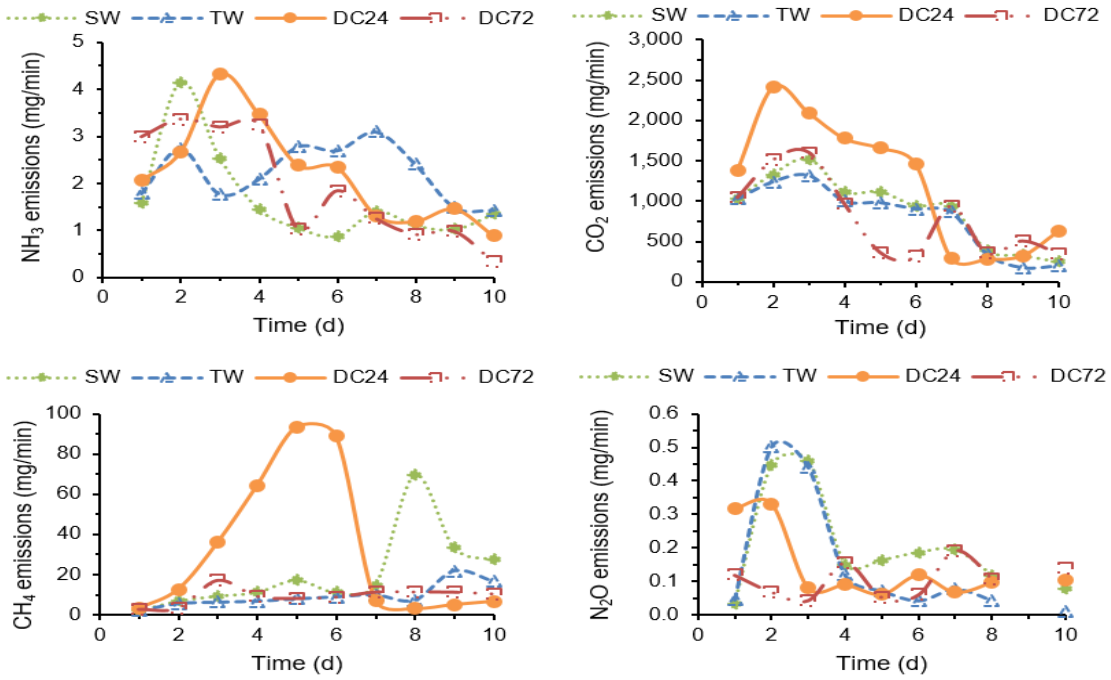

Figure 4. Daily mean emissions of ammonia (NH_3), carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) over 10 d in rooms containing RMS following different treatments: static windrow (SW), turned windrow (TW), drum composter for 24 h (DC24), or drum composter for 72 h (DC72).

At day 0, important concentrations of microbial and total dust were detected as pipes were loading with fresh RMS or drum-composted RMS (Figure 5). SW RMS-associated air showed lower concentrations of airborne culturable mesophilic bacteria (4.0×10^3 cfu/m^3 of air) than DC72 RMS (9.7×10^4 cfu/m^3 of air). Bacterial concentrations associated with SW and TW were below the Poland recommendation of 10^5 cfu/m^3 for bacteria (Dutkiewicz, 1997), while DC24 and DC72 reached that suggested exposure limit value. DC72 was as well characterized by the highest airborne culturable mesophilic fungi (5.6×10^4 cfu/m^3 of air) and the highest total dust concentration (0.137 mg/m^3 of air). Following 5 d of composting in pipes, concentrations of all studied microorganisms and dust decreased as airborne particles settled down (Figure 5). However, SW still showed lower concentrations of culturable mesophilic bacteria (1.9×10^1 cfu/m^3 of air) than DC72 (1.5×10^3 cfu/m^3 of air). DC72 reached one of the recommended TLV-TWA of 10^3 cfu/m^3 for bacteria (Marchand et al., 1995). Concentrations of culturable mesophilic fungi were higher in DC24 and DC72 experimental rooms (6.9×10^2 and 1.2×10^3 cfu/m^3 of air, respectively) than in the ones of SW and TW treatments (3.3×10^2 and 3.0×10^2 cfu/m^3 of air, respectively). Total dust concentrations were more important for SW and TW treatments (0.027 and 0.028 mg/m^3 of air, respectively) than for DC24 and DC72 (0.012 and 0.018 mg/m^3 of air, respectively). Ten days after loading pipes with RMS, DC72 treatment still showed higher concentrations of culturable mesophilic bacteria (3.3×10^3 cfu/m^3 of air) than SW treatment (4.8×10^2 cfu/m^3 of air; Figure 5). Bacterial concentrations for the SW treatment were below the recommended TLV-TWA of 10^3 cfu/m^3 of air (Marchand et al., 1995). After 10 d, no difference was observed between composting approaches for culturable mesophilic fungi and concentrations were all below the proposed exposure limit value of 5×10^4 cfu/m^3 (Dutkiewicz, 1997), but total dust concentrations for DC72 (0.064 mg/m^3 of air) were higher than SW and TW rooms (0.008 and 0.015 mg/m^3 of air,

respectively). Concentrations of airborne thermotolerant fungi did not differ on each sampling day for all studied composting approaches. While not impacting airborne microbial concentrations, manual turning of composted TW RMS did increase total dust concentrations on day 10, passing from 0.015 (before) to 0.073 (during) mg/m^3 of air. The Canadian Center for Occupational Health and Safety threshold limit value – time-weighted average (TLV-TWA) of 10 mg/m^3 of air for total dust (Donham et al., 1989) was never attained throughout the 10-d experimental period for all composting approaches.

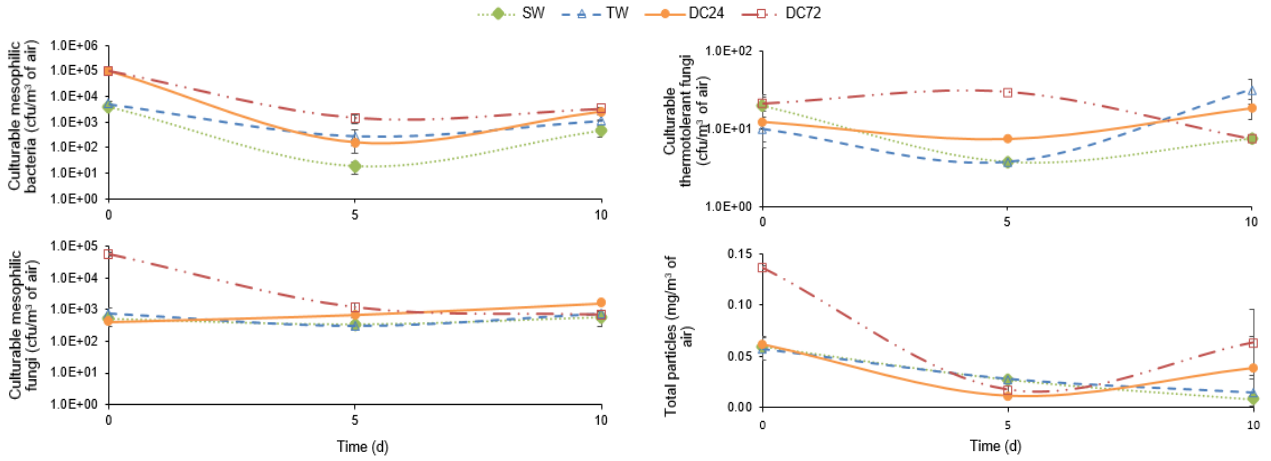

Figure 5. Culturable mesophilic bacteria, culturable mesophilic fungi, culturable thermotolerant fungi, and total dust over 10 d in experimental rooms containing RMS following different treatments: static windrow (SW), turned windrow (TW), drum composter for 24 h (DC24), or drum composter for 72 h (DC72).

Conclusion

Considering that separator type did not have a major influence on the chemical and bacteriological composition of produced RMS, the choice of a separator for Canadian dairy producers should be based on cost capacity, energy use, separation efficiency, DM content, structure of RMS, and the fertilizing quality of the separated liquid. On one side, the decanter centrifuge obtained the greatest concentration of DM in the solid phase and separation efficiencies for DM, N, and P. However, its low treatment capacity combined with its high acquisition cost and energy consumption reduce its technical value and make it hardly profitable for producers. Besides, the centrifuge produced fine-textured RMS not suitable for use as dairy cow bedding. On the opposite side, presses reached acceptable volumetric flow rates at a minimal operating cost. They can also achieve recommended DM content in RMS (> 30%) according to the present results for the roller press or by Valacon-Dairy (2014) for the screw press. Therefore, the choice between the presses would depend on separation efficiency and RMS structure. The roller press has the advantages to be flexible in terms of inputs (initial DM content and particle size distribution) and to produce a fluffy solid material with ideal properties for bedding (comfort and drying potential). Nevertheless, its compression process seems to favor more easily the passage of solids into the liquid fraction so that a greater quantity of slurry manure is needed to produce the same quantity of RMS than the screw press.

Since physico-chemical properties did not change enough between treatments during the 10-d period in piles to be a major decision factor, the recommendation for an efficient composting method should essentially be based on reaching and maintaining a thermophilic temperature in RMS, reducing bacteria in RMS, and limiting aerosolization of dust particles and microbes. Each treatment reached the minimal temperature (either in the drum composter or in heaps), so reductions in bacteria would be a better indicator of the sanitation efficiency. The passage of fresh RMS into a drum composter for 24h was the fastest way to reduce *E. coli* (from 5.0 to 1.3 $\log_{10}$ cfu/g of DM) and *Klebsiella* spp. (from 4.5 to 2.6 $\log_{10}$ cfu/g of DM) levels. Increasing the time RMS were in the rotating vessel to 72 h did not result in further decreases of these microorganisms. The other treatments consisting in windrow composting only (SW and TW) achieved similar *E. coli* and *Klebsiella* spp. reductions to drum composting but in 5 or 10 d. That could represent an increased workload (pile turning) and an economic burden (storage area) for dairy farmers, in the same ways as the purchase and operation of a drum composter. Otherwise, counts in *Staphylococcus* spp., *Streptococcus* spp., and *Enterococcus* spp. did not show clear differences between composting approaches. Heaping of drum-composted RMS did not result in any additional sanitation. The static composting of DC24 and DC72 also did not reveal any issue regarding gas emissions relative to SW or TW. Drum-composted RMS may then be stored some days before being used as bedding. The air quality in SW and TW experimental rooms was, however, better than in the one for treatment of drum-composted RMS.

Finally, according to the present study, Canadian dairy farmers should be oriented towards press separation and drum composting of RMS for 24 h to produce high quality RMS.

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