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Production of recycled manure solids for use as bedding in Canadian dairy farms: II. Composting methods

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ABSTRACT

Recent technological advances in the dairy industry have enabled Canadian farms with liquid manure systems to use mechanical solid-liquid separation paired with composting of the separated solids for on-farm production of low-cost bedding material. However, because several approaches are available, it is difficult for farmers to select the appropriate one to achieve high quality recycled manure solids (RMS). Whereas 3 solid-liquid manure separators were compared in part I of the series (companion paper in this issue), the present study (part II) aims to assess the performance of 4 composting methods (static or turned windrow and drum composter for 24 or 72 h) under laboratory conditions. Parameters evaluated included temperature, physico-chemical characteristics, and bacterial composition of RMS, as well as airborne microorganisms, dust, and gases associated with composting RMS. Because each treatment attained the desired composting temperature range of 40 to 65°C (either in heaps or in the drum composter), reductions in bacteria were a better indicator of the sanitation efficiency. The treatment of fresh RMS in a drum composter for 24 h showed decreased bacterial counts, especially for *Escherichia coli* (from 1.0×10^5 to 2.0×10^1 cfu/g of dry matter) and *Klebsiella* spp. (from 3.2×10^4 to 4.0×10^2 cfu/g of dry matter). Increasing the time spent in the rotating vessel to 72 h did not result in further decreases of these pathogens. Composting in a static or turned windrow achieved similar *E. coli* and *Klebsiella* spp. reductions as the 24-h drum composting but in 5 or 10 d, and generally showed the lowest occupational exposure risk for dairy farmers regarding concentrations of airborne mesophilic bacteria, mesophilic and thermotolerant fungi, and total dust. Drum-composted RMS stored in piles exhibited intermediate to high risk. Composting approaches did not have a major influence on the physico-chemical characteristics of RMS and gas emissions. Drum composting for 24 h was the best compromise in terms of product quality, temperature reached, decreased bacterial numbers, and emitted airborne contaminants. However, because levels of pathogenic agents rapidly increase once composted RMS are spread in stalls, bacteriological characteristics of RMS along with milk quality and animal health and welfare features should be monitored in Canadian dairy barns applying recommended separation (part I) and composting (part II) systems to evaluate health risk and optimize management practices.
Key words: cattle, compost characteristics, bacterial counts, air quality

INTRODUCTION

Methods to separate the solid fraction of cow manure slurry have been known for a while and the use of the dewatered material as bedding on dairy farms is increasing in popularity (Garcia and Diaz-Royón, 2014; Leach et al., 2015; House, 2016). Following solid-liquid separation, fresh recycled manure solids (**RMS**) may be used directly in stalls without treatment or subjected to a hygienization procedure before being used as bedding (Harrison et al., 2008; Husfeldt et al., 2012; Cole, 2015).

Due to high bacterial concentrations in RMS in comparison with common bedding sources, concerns have been raised about fresh RMS posing a health risk for animals and humans, especially in wet and cold areas such as Canada (Leach et al., 2015; Bradley et al., 2018). Thus, composting the slurry solid fraction could be advantageous as it involves thermophilic microorganisms (bacteria, fungi, and so on) breaking down OM aerobically in an oxygen-filled environment (Larney et al.,

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2006; Bernal et al., 2009; Keener, 2011; House, 2016). At temperatures between 40 and 65°C, this process results in maximal destruction of enteric pathogens, microbial stabilization, and reduction of moisture (Bernal et al., 2009; Brito et al., 2012; Cole, 2015; Bonifacio et al., 2017a). Moreover, Carroll and Jasper (1978), Bishop et al. (1981), Harrison et al. (2008), Husfeldt et al. (2012), and Cole (2015) demonstrated that before use, fresh RMS contained greater total counts of bacteria than composted RMS. Therefore, composting is justified as manure needs to be partially sterilized (Parkinson et al., 2004).

Composting fresh RMS has been done for many years on dairy farms in Canada (Ontario: House, 2016; Quebec: Parent, 2017) and in the United States (New York: Harrison et al., 2008; Ohio: Cole, 2015; Wisconsin, Minnesota, South Dakota, and Iowa: Husfeldt et al., 2012). Nevertheless, composted RMS cannot be used in the United Kingdom (APHA, 2016) and European Union (The European Parliament and The Council of the European Union, 2009) because composting has been associated with counts of spore-forming, heat-resistant bacteria in farms' milk tank in some studies (Driehuis et al., 2012; Driehuis et al., 2014; Miller et al., 2015). These spores can reduce the shelf life of pasteurized milk products and lead to losses during cheese production, but pose no health risk for consumers (Driehuis et al., 2014; APHA, 2016). Composting animal manure is also associated with the loss of large amounts of N, through ammonia (NH_3) and nitrous oxide (N_2O) volatilization (Brito et al., 2008; Bonifacio et al., 2017a), and production of airborne dust particles and microbes, which have the potential to cause respiratory problems such as allergies, asthma, chronic bronchitis, or hypersensitivity pneumonitis to dairy producers (Schenker et al., 1998; Lee et al., 2006).

Fresh RMS can be composted in static piles for 3 to 10 d (Harrison et al., 2008), in windrows turned every few days for 2 wk (Timms, 2008), or through mechanical drum-composting for 18 to 72 h (Harrison et al., 2008; Husfeldt et al., 2012; House, 2016). Further decomposition in heaps is often necessary for drum-composted matter to reduce phytotoxicity (Rynk et al., 1992; Heinonen-Tanski et al., 2006). Static piles are less labor-intensive than turned-windrow composting. Their insulation layer and lack of turnings also conserve N and limit the release of NH_3 and odors. However, turning of RMS is one way to increase the oxygen content in the inner parts of heaps, leading to a reduction in enteric microorganism numbers. In-vessel composting usually carries greater acquisition and operation costs than static and turned windrows, but it enables faster composting and consistent RMS quality (Rynk et al., 1992; Heinonen-Tanski et al., 2006).

Reports comparing the aforementioned approaches for RMS under a humid continental climate in controlled experimental conditions are limited (Cole, 2015). Using published data from an independent cattle manure composting experiment, Bonifacio et al. (2017b) demonstrated that the ranges of values for measured chemical characteristics and greenhouse gas emissions did not considerably vary between static and turned piles. Brito et al. (2008) showed that these 2 composting methods had similar temperature patterns during a period of 150 d. According to past studies (Table 1), there are no clear differences between composting techniques in terms of bacterial counts.

At this time, the best composting method for RMS is unknown and Canadian dairy producers' decisions are often directed and influenced by the farm equipment industry. Therefore, the present study aimed to assess the performance (temperature and composition of RMS, and the associated air quality) of 4 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

Experimental Setup

A 2-wk experiment was conducted from July 3 to 14, 2017, at the Centre de recherche en sciences animales de Deschambault (**CRSAD**; Deschambault, QC, Canada) in a research facility consisting of 12 independent bench-scale rooms (1.2 m width × 2.4 m length × 2.4 m height) side by side. Each room was equipped with a variable-speed exhaust fan. The incoming air, drawn from outside the facility, was the same for all the rooms and came from a main duct in which the air was 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, which represented the average maximum temperature in Deschambault during the summer months of the past 5 yr (Environment Canada, 2018).

On the concrete floor of each room, a 3-section polyethylene drainage pipe (1.5 m deep and 0.75 m in diameter) with a smooth interior wall and a corrugated exterior wall (Figure 1c) was installed to contain 0.67 m^3 of RMS. 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

4 following composting approaches was randomly attributed through drawing lots to each of the 12 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.

Experimental Design

On the first day of the experiment, a temporary 5.5-m diameter slurry tank, made of recycled corrugated steel silo sheets coated with a geosynthetic membrane, was filled with fresh manure from the in-barn storage pit of a nearby dairy farm using RMS for 5 yr. The

Table 1. Bacterial counts in composted recycled manure solids (RMS) using static windrows (SW), turned windrows (TW), or a drum composter (DC) in original[1] and converted units

	Harrison et al. (2008)		Timms (2008)	Husfeldt et al. (2012)	Cole (2015)
Item	SW[2]	DC[3]	TW[4]	DC[5]	TW[6]
Count (log_{10} cfu/mL)					
Bacillus spp.				(3.90)	
Coliforms	(0.00)	(0.00)	0.60	(0.00)	0.32
Corynebacterium spp.	(1.10)	(0.90)			
Enterobacter	(0.00)	(0.00)			
Gram-negative bacteria	(8.60)	(12.00)	1.80		0.62
Gram-positive bacteria	(12.20)	(13.70)			
Klebsiella spp.	(1.00)	(0.00)			0.29
Proteus spp.	(0.50)	(0.00)			
Staphylococcus spp.	(0.00)	(0.00)		(1.02)	
Streptococcus spp.	(7.20)	(7.00)	1.50	(4.00)	0.46
Count (log_{10} cfu/g)					
Bacillus spp.				19.52	
Coliforms	0.00	0.00	(2.00)	0.00	0.92
Corynebacterium spp.	3.14	3.60			
Enterobacter	0.00	0.00			
Gram-negative bacteria	24.57	48.00	(6.00)		1.77
Gram-positive bacteria	34.86	54.80			
Klebsiella spp.	2.86	0.00			0.84
Proteus spp.	1.43	0.00			
Staphylococcus spp.	0.00	0.00		5.12	
Streptococcus spp.	20.57	28.00	(5.00)	20.00	(1.31)
Count (log_{10} cfu/g of DM)					
Bacillus spp.				49.17	
Coliforms	0.00	0.00	6.67	0.00	(3.34)
Corynebacterium spp.	11.51	9.92			
Enterobacter	0.00	0.00			
Gram-negative bacteria	90.01	132.23	20.00		(6.45)
Gram-positive bacteria	127.68	150.96			
Klebsiella spp.	10.47	0.00			(3.04)
Proteus spp.	5.23	0.00			
Staphylococcus spp.	0.00	0.00		12.91	
Streptococcus spp.	75.35	77.13	16.67	50.38	(4.75)

[1]Numbers in parentheses represent original values.

[2]Fresh RMS composted in windrows in a building for 10 d (27.3% DM and density assumed at 350 kg/m^3 based on part I (Fournel et al., 2019) results at this DM content).

[3]Fresh RMS composted in a DC for 24 h and piled for 1 d (36.3% DM and density assumed at 250 kg/m^3 based on part I (Fournel et al., 2019) results at this DM content).

[4]Screen-separated RMS composted in windrows outside for 2 wk and turned every few days (30.0% DM and density assumed at 300 kg/m^3 based on part I (Fournel et al., 2019) results at this DM content).

[5]Screw-separated RMS composted in a DC for 18 to 24 h (39.7% DM and density assumed at 200 kg/m^3 based on part I (Fournel et al., 2019) results at this DM content).

[6]Screw-separated RMS composted in windrows outside for 4 wk and turned weekly (27.5% DM and density assumed at 350 kg/m^3 based on part I (Fournel et al., 2019) results at this DM content).

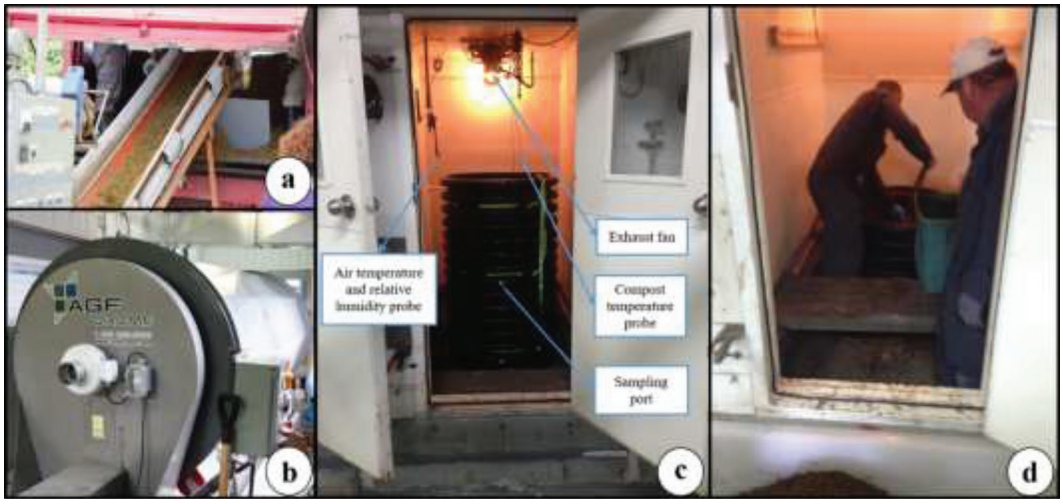

Figure 1. Production, composting, and management of recycled manure solids (RMS): (a) loading of the silage trailer with freshly separated RMS; (b) drum-composting of a part of RMS produced; (c) charging 1 of the 12 drainage pipes inside the experimental rooms with fresh or drum-composted RMS; and (d) daily discharging of pipes involved in the turned windrow treatment.

slurry manure was then mechanically separated using a screw press (FAN model PSS 2–520, Bauer Group, Michigan City, IN). A more detailed description of this separator can be found in the first part of the series.

Newly separated RMS were loaded in a silage trailer (Figure 1a) to transport the material to the research facility. Approximately 6 m^3 of fresh RMS were produced on the first day. One-third of the production was used to fill the pipes of the 3 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 × 3 m length; AGF Brome, Cowansville, QC, Canada) located in a CRSAD building (Figure 1b). The drum, equipped with a circular inline duct fan (model CK 4" A, Östberg, Cambridge, ON, Canada) producing a flow up to 60 L/s, turned continuously with a delay of 10 s between each full rotation. The process lasted 24 h to complete the DC24 treatment.

On the following day, the drum composter was emptied and the material was transported to the DC24 experimental rooms and loaded into the appropriate pipes. Given that drum composting increased the density of RMS (see the Results and Discussion section), only 2 pipes out of 3 were completely filled. One DC24 room was therefore excluded from the experiment. 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. Similarly to DC24 treatment, one room was excluded from the experiment because a third pipe could not be completely filled.

Recycled manure solids remained static in the pipes for 10 d for treatments SW, DC24, and DC72. For the TW treatment, RMS were turned daily in the morning by discharging manually with a shovel all the content of the cylinders and by reloading them, ensuring that top and bottom material were inverted (Figure 1d).

Data Collection

Laboratory Analyses of RMS. Recycled manure solids were sampled on 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 in the pipes (all treatments). Sterile disposable plastic scoops were used to randomly sample each 2 m^3 of RMS produced and each type of drum-composted RMS on d 0, whereas sampling of RMS on d 5 and 10 for all treatments was done by inserting a core drill into the 3 fixed sampling ports created on the pipes.

Samples of RMS (between 0.5 and 1.0 L) were collected for physical, chemical, and bacteriological analyses. Each sample was kept at 4°C until analysis. Physical (bulk density, water absorption, porosity, and particle size distribution), chemical [pH, DM, ash, OM, C, total Kjeldahl N (**TKN**), NH_4-N, and organic N], and bacteriological (*Escherichia coli*, *Klebsiella* spp., *Staphylococcus* spp., *Streptococcus* spp., and *Enterococcus* spp.) analyses were performed following the methods presented in Table 1 of the companion paper (Fournel et al., 2019).

RMS and Air Temperature, Relative Humidity, and Ventilation Rate. In each room, the tem-

perature of the composted RMS and air was measured using 2 type T thermocouples inserted into RMS at different locations (middle of top and bottom half) and a probe equipped with a 1,000 Ohm platinum resistance thermometer (model CS500, Campbell Scientific Canada, Corp., Edmonton, AB, Canada) suspended from the ceiling, respectively. The suspended probe also contained a humidity sensor to evaluate the relative humidity of the air. Instruments were connected to a data logger (CR1000 model, Campbell Scientific, Edmonton, AB, Canada). Data were uploaded every 5 s and the average recorded every 15 min.

Ventilation rates were calculated from a 204-mm iris orifice damper (model 200, Continental Fan Manufacturing Inc., Buffalo, NY) installed in the exhaust duct of each room. A difference of pressure was measured across the damper every 5 s and the data logger recorded the average every 15 min. The average value was then used to calculate the ventilation rate using Equation 1 in Fournel et al. (2011).

Gas Emissions. Gases from each room were pumped to a mobile laboratory through Teflon tubing. Ammonia was analyzed by a nondispersive infrared analyzer (Ultramat 6E model, Seimens, Munich, Germany), and greenhouse gases were analyzed by GC (model 3600, Varian, Walnut Creek, CA). For chromatographic analysis, the 3 gases were separated in columns packed with Porapak Q (Waters Corporation, Milford, MA). Carbon dioxide (CO_2) and N_2O were measured with an electron capture detector. Methane (CH_4) was quantified with a flame ionization detector. Samples were pumped from the experimental rooms through the injection loop of the nondispersive infrared analyzer and GC for 15 min, before being analyzed. A multiport valve was used to cycle gas sampling between the different rooms every 15 min. Concentration measurements were taken continuously during the entire experiment and were synchronized with the ventilation flow rate. A data logger recorded the value measured by the analyzers. The emissions were then calculated for each sampling period by multiplying the difference in concentration by the mass flow of the gas (Equation 2 in Fournel et al., 2011).

Airborne Microbial and Dust Concentrations. Airborne microorganisms and dust concentrations were sampled in each room 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) was used to collect microbes in 15 mL of PBS (Lonza, Walkersville, MD) at a flow rate of 200 L/min for 10 min (2 m^3 of sampled air). Airborne dust particles were measured with a DustTrak DRX Aerosol Monitor (model 8534, TSI, St. Paul, MN) at a flow rate of 3 L/min for 10 min.

Air was sampled in each room at d 0 when pipes were loaded. Air sampling was also done at d 5 and 10 for SW, DC24, and DC72 treatments. For TW treatment, 2 samples were taken at d 5 and 10: one before and one during RMS turning. A delay of 5 min was allowed between the moment both air samplers were installed in the rooms and the beginning of the sampling at d 5 and 10 (except for TW rooms when RMS were refilled into the pipes) to achieve a certain steady-state environment after the door was opened.

Ten-fold serial dilutions of the Coriolis μ samples were plated on different culture medium to determine airborne culturable microbial content. Mesophilic bacteria were counted from plates of Difco Tryptic Soy Agar (BD, Sparks, MD) with 5 μg/mL amphotericin (Sigma-Aldrich, St. Louis, MO) incubated at 25°C for 3 d. Mesophilic fungi were cultivated at 25°C on Difco Rose Bengal Agar (BD) with 50 μg/mL of 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.

Statistical Analyses

A linear mixed model (SAS v9.4, SAS Institute Inc., Cary, NC) was built to assess composted RMS characteristics, environmental parameters, airborne microbes and dust, and gas emissions. The treatment, day, and interaction between treatment and day were the fixed explanatory variables used in the model. Day effect was considered as an effect of repeated measures, and the correlation structure between observations within a day and an experimental room was also modeled. The room was analyzed as a random effect.

Another linear mixed model was used to evaluate variance of composted RMS temperature. Besides the nature of the treatment and the day, the thermocouple position (top or bottom) was a fixed effect, as well as double and triple interactions between these factors. Day and position effects were repeated measures in time and the correlation structure between observations within an experimental room was modeled. The room and the interaction room by day were analyzed as random effects.

For composted RMS temperature and characteristics, environmental parameters, and gas emissions, *F*-test values, means, standard deviations, and 95% confidence intervals were calculated for each fixed effect. Multiple comparisons of least squares means (*t*-test) between days were also completed. Normality and homogeneity of variance were visually evaluated using residual plots.

For airborne microbes and dust, different statistical models were applied to obtain the best-fit model for

covariance structure and likelihood ratio tests were carried out among models. Comparisons of Akaike's information criterion for the different models were also obtained. The univariate normality assumption was verified with the Shapiro-Wilk tests on the error distribution from the statistical model after a Cholesky factorization. Brown and Forsythe's variation of Levene's test statistic was used to verify the homogeneity of variances. All variables were log-transformed to fulfill the model assumptions and reported *P*-values are based on these transformations. For variables with nondetectable values (left censored), a nonparametric mixed statistical model on longitudinal data proposed by Brunner et al. (2002) was performed.

RESULTS AND DISCUSSION

Physical, Chemical, and Bacteriological Characteristics of Fresh RMS

The composting process is influenced by several factors such as moisture content, C/N ratio, pH value, and physical structure of the raw material (Brito et al., 2008). Because the RMS for the DC72 treatment were produced 1 d later than those for the other treatments, due to availability of the drum composter (only one on CRSAD farm), we compared the initial physical, chemical, and bacteriological characteristics of fresh RMS produced by separation (Table 2).

The chemical content of the fresh RMS used for DC72 was essentially the same as that used for SW, TW, and DC24. Parameter values for pH (8.0–8.5), DM (25.0–25.5%), ash (9.7–10.5%), C (447–452 g/kg of DM), and TKN (19.4–20.0 g/kg of DM) were in the same range for all fresh RMS. However, we observed slight differences in terms of density (DC72 vs. other treatments: 354 vs. 381 kg/m^3), absorption (118 vs. 103 g/100 g), and porosity (74.4 vs. 72.5%). Fresh RMS produced for the DC72 treatment also contained more fine and medium particles than the fresh RMS used for SW, TW, and DC24 (53.4 vs. 49.0%).

Bacterial counts measured in fresh RMS sampled following separation and before pipe filling were consistent as Table 2 results for SW, TW, and DC24 RMS (3.2×10^4 to 1.6×10^6 cfu/g of DM for the 5 species) were comparable to those of DC72 RMS (1.6×10^4 to 2.0×10^6 cfu/g of DM for the 5 species). These concentrations agreed with the observations made in the companion paper (Fournel et al., 2019) with the screw press and data reported by Leach et al. (2015).

Physical, Chemical, and Bacteriological Characteristics of Composted RMS

Physical Properties. Figures 2 and 3 illustrate physical properties of RMS 0, 5, and 10 d after being loaded in the pipes. Drum-composted material at 0 d (the beginning of the static composting period) had a

Table 2. Physical, chemical, and bacteriological properties of recycled manure solids following separation for each tested composting method: static windrow (SW), turned windrow (TW), drum composter for 24 h (DC24), and drum composter for 72 h (DC72)

Analysis type and property	SW	TW	DC24	DC72
Physical				
Density (kg/m^3)	392.5	372.0	379.7	354.4
Absorption (g/100 g)	102.2	104.4	101.7	118.2
Porosity (%)	71.9	72.7	72.9	74.4
Particle size distribution (%)				
<1 mm	0.8	1.2	1.5	1.8
1–4 mm	46.1	49.8	47.5	51.6
>4 mm	49.3	45.2	47.2	42.7
Chemical				
pH	8.3	8.4	8.0	8.5
DM (%)	25.0	25.3	25.0	25.5
Ash (%)	9.7	10.5	9.8	10.1
OM (%)	90.4	89.5	90.0	89.9
C (g/kg of DM)	451.7	447.7	451.0	449.0
Total Kjeldahl N (g/kg of DM)	19.6	20.0	19.6	19.4
NH_4-N (g/kg of DM)	3.2	2.9	5.2	4.3
Organic N (g/kg of DM)	16.4	17.1	14.4	15.0
C/N	23.3	23.0	23.2	23.9
Bacteriological				
Escherichia coli ($\log_{10}$ cfu/g of DM)	5.0	5.0	5.0	4.8
Klebsiella spp. ($\log_{10}$ cfu/g of DM)	4.5	4.5	4.5	4.2
Staphylococcus spp. ($\log_{10}$ cfu/g of DM)	6.0	6.0	6.0	6.1
Streptococcus spp. ($\log_{10}$ cfu/g of DM)	6.2	6.2	6.2	6.3
Enterococcus spp. ($\log_{10}$ cfu/g of DM)	6.1	6.1	6.1	6.0

greater density ($P < 0.001$) than SW and TW material (536 vs. 382 kg/m^3 on average). The difference was due to the high moisture content of fresh RMS (Table 2) combined with the continuous rotation movement of the drum composter, which caused the formation of solid, 1-cm-diameter balls of material inside the vessel. On d 5 and 10, we observed a 5 to 20% decrease of density in SW, DC24, and DC72 composted materials because of OM decomposition involving a reduction of the weight of the piles (Bernal et al., 2009). In contrast, TW compost increased in density throughout the experiment, from 372 to 433 kg/m^3. This could be the result of compaction created by very frequent manual turning.

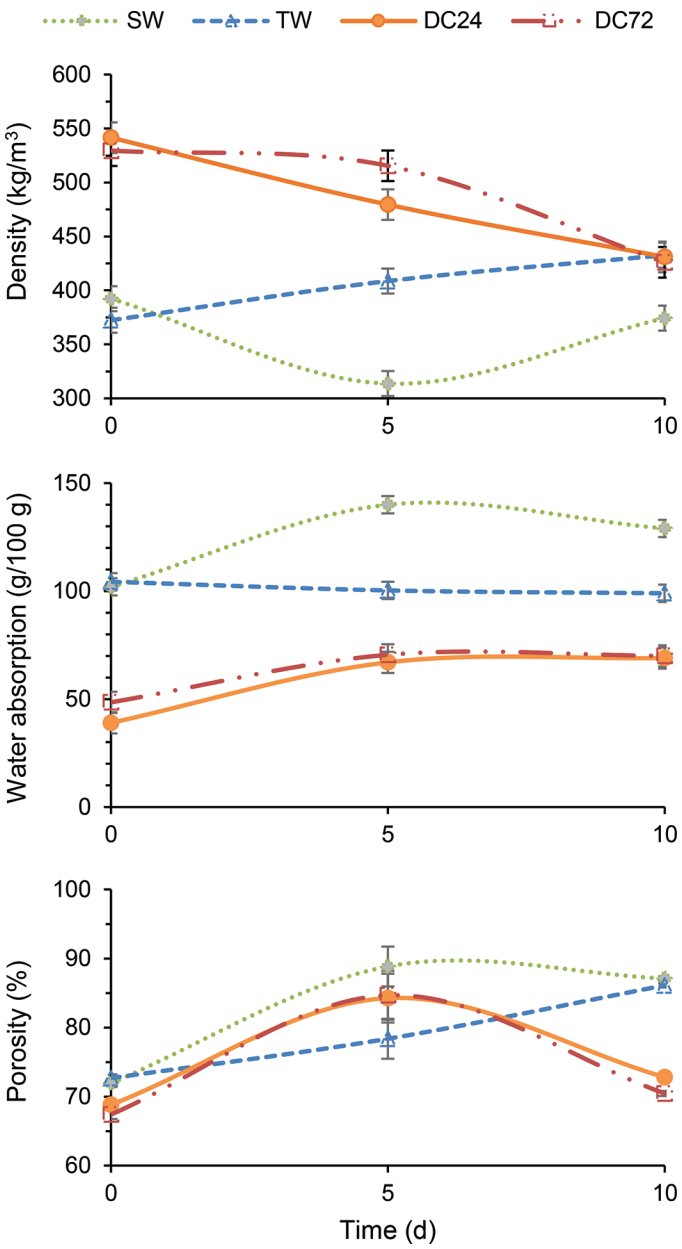

Figure 2. Mean density (top), water absorption (middle), and porosity (bottom) of composted recycled manure solids on d 0, 5, and 10 following different treatments: static windrow (SW), turned windrow (TW), drum composter for 24 h (DC24), or drum composter for 72 h (DC72). Error bars represent SE.

The formation of solid balls during drum composting also affected water absorption ($P < 0.001$). At 0 d, drum-composted materials could absorb less than 50 g of water per 100 g of RMS compared with more than 100 g of water per 100 g of RMS for SW and TW treatments. On the fifth day of pile composting, RMS in SW, DC24, and DC72 pipes had a slightly improved absorption, whereas that of the TW was unchanged. We noted no substantial difference in water absorption between d 5 and 10 for all composting approaches.

Material porosity during the first 5 d of pile composting followed the same pattern for all composting approaches, increasing from about 70% to 84% ($P < 0.001$). On d 10, SW and TW porosities were comparable (87%), whereas those of drum-composted RMS dropped to their initial level (72%).

Particles with a diameter less than 1 mm were almost absent in any composted RMS as they represented less than 3% of the samples. Medium- and large-size particle distribution depended on whether RMS passed into the drum composter or not. Both drum-composted treatments contained a greater proportion of coarse particles compared with SW and TW treatments (72 vs. 44%). The RMS from SW and TW were mainly composed of medium particles (52%).

Chemical Properties. Table 3 presents the chemical characteristics of piled RMS composted by the 4 different approaches. Regardless of the treatment, pH was alkaline, varying between 8.3 and 8.5 throughout the experiment. These values were within the reported range of 6.9 to 9.6 for 14 d of composting (Cáceres et al., 2006; Brito et al., 2008; Brito et al., 2012) and within the recommended pH conditions (6.7–9.0) supporting microbial activity during composting (Bernal et al., 2009; Keener, 2011).

Statistically significant differences were observed in DM content between composting approaches ($P < 0.05$). The static composting in pipes of drum-composted RMS tended to have a drying effect (+1.0–1.5 percentage units) when comparing DM results in Table 3 with those directly after separation (Table 2). Moisture reduction through evaporation losses is a key benefit of the composting process (Brito et al., 2008; Bernal et al., 2009). The SW piles also had a minor increase in DM, whereas it slightly decreased within the TW pipes. Similarly, Brito et al. (2008) observed a differ-

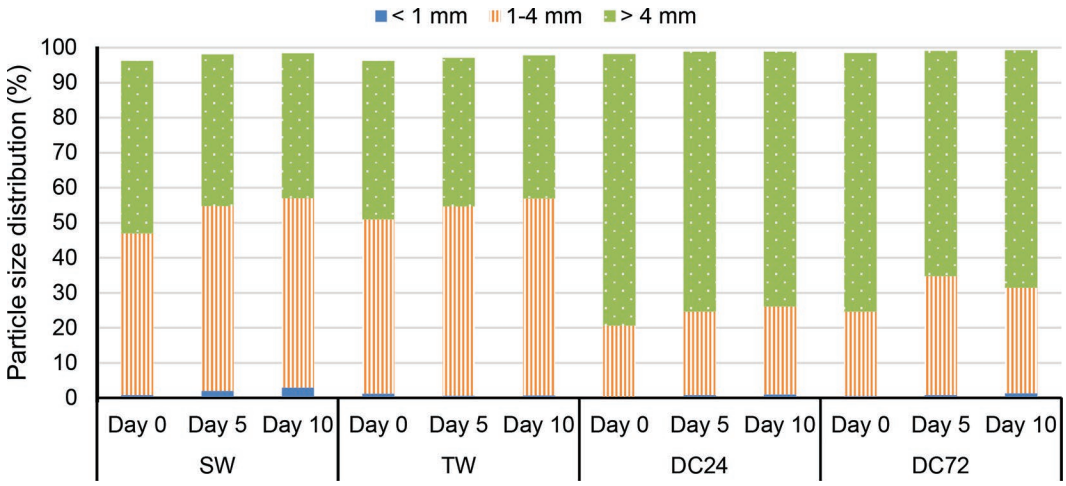

Figure 3. Particle size distribution of composted recycled manure solids on d 0, 5, and 10 following different treatments: static windrow (SW), turned windrow (TW), drum composter for 24 h (DC24), or drum composter for 72 h (DC72).

ence of 2 percentage units after 14 d of composting in static (decrease) and turned (increase) piles with an initial DM content of 24.9%. Overall, the DM values in the present study were outside the optimal range (30–50%) supporting effective microbial activity (Brito et al., 2008, 2012) and recommendations for RMS use as bedding for dairy cows (APHA, 2016; Bradley et al., 2018). Although 25 to 27% DM conditions are not critical for enabling oxygen diffusion into the piles to maintain aerobic process (Bernal et al., 2009; Keener, 2011), a drier material after separation could have led to different results in terms of water absorption, porosity, particle size distribution, drying potential, bacterial reductions, and emissions (see next sections for the latter 2 items). Ultimately, the suitability of these screw-separated RMS, even composted, can be questionable.

Ash (10.5–11.1%), OM (88.9–89.5%), and C (44.4–44.8%) concentrations did not significantly ($P > 0.05$) differ between treatments. Only the day factor influenced ($P < 0.001$) these properties over the 10-d period in heaps (Figure 4). As would be expected, ash proportion increased with time as OM was decomposed by microorganisms within RMS. Because C is related to OM, its content dropped from approximately 450 to 441 g/kg of DM. As a consequence of OM breakdown and thus C loss (Brito et al., 2008, 2012), C/N ratio declined for all composting treatments, falling from 23.4 on average at the beginning of the 10-d composting process (Table 2) to 21.8 on average toward the end of the experiment (Table 3).

As reported by Brito et al. (2008), total N concentration increased with decreasing OM content. Thus, TKN increased significantly ($P < 0.001$) from 19.7 to 23.9 g/kg of DM in 10 d of composting (Figure 5). However, although Brito et al. (2008) found that turning was associated with increased N content, the TW composting approach in the present study had the lowest ($P < 0.05$) N concentration. Turning frequency was likely not

Table 3. Average chemical properties of recycled manure solids sampled at d 0, 5, and 10 according to each tested composting approach: static windrow (SW), turned windrow (TW), drum composter for 24 h (DC24), and drum composter for 72 h (DC72)

Item	SW	TW	DC24	DC72
pH	8.3^{c}	8.5^{a}	8.5^{ab}	8.4^{bc}
DM (%)	25.6^{b}	24.8^{b}	26.0^{ab}	27.0^{a}
Ash (%)	11.0^{a}	10.9^{a}	11.1^{a}	10.5^{a}
OM (%)	89.1^{a}	89.1^{a}	88.9^{a}	89.5^{a}
C (g/kg of DM)	445.2^{a}	445.4^{a}	444.0^{a}	447.5^{a}
Total Kjeldahl N (g/kg of DM)	21.5^{b}	20.3^{c}	22.6^{a}	21.9^{ab}
NH_4-N (g/kg of DM)	2.7^{a}	2.8^{a}	2.0^{b}	2.1^{b}
Organic N (g/kg of DM)	18.8^{b}	17.4^{c}	20.6^{a}	19.8^{a}
C/N	21.7^{ab}	22.2^{a}	20.9^{b}	22.5^{a}

$^{a–c}$Means within a row with different superscripts differ ($P < 0.05$).

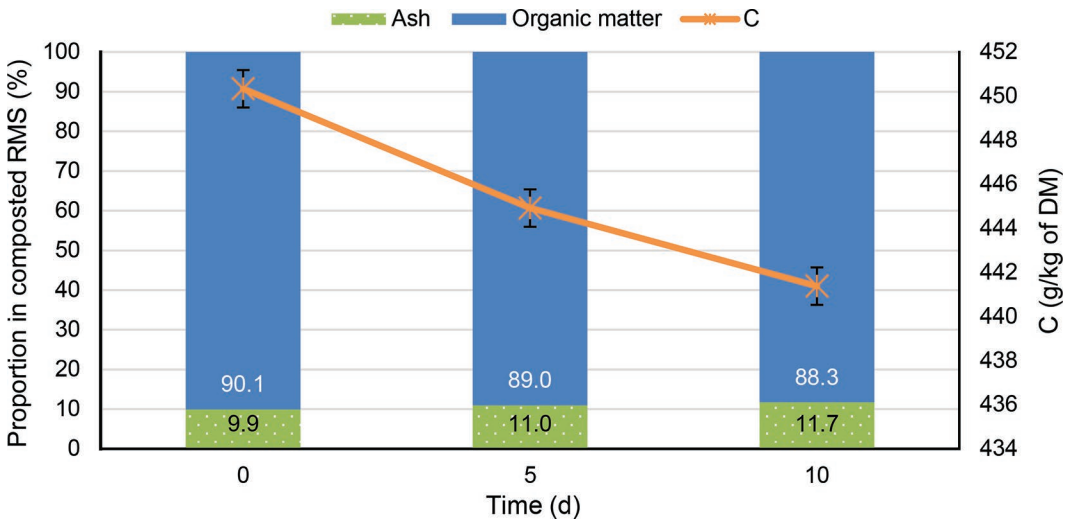

Figure 4. Mean proportion of ash and OM and concentration of C in composted recycled manure solids (RMS) on d 0, 5, and 10 of the composting period. Error bars represent SE.

optimal. Organic N followed the same trend as TKN, which slightly increased with time (Figure 5), as reported by Brito et al. (2012).

Mineral N content of composted RMS in the pipes was characterized by near-zero nitrates (NO_3-N) and elevated ammonium (NH_4-N) contents. Elevated temperature and CO_2 concentrations inhibit nitrifier activity during the initial stages of composting (Brito et al., 2008). Values for ammonium (2.0–2.8 g/kg of DM) were comparable to similar studies (Cáceres et al., 2006; Brito et al., 2008, 2012) on dairy manure composting (0.0–3.0 g/kg of DM). The authors also noted a marked decrease in NH_4-N over time, which is apparent in Figure 5 as the concentration halved ($P < 0.05$) from d 0 (3.2 g/kg of DM) to 10 (1.6 g/kg of DM). The reduction of ammonium content can be attributed to the assimilation processes carried out by the microorganisms and volatilization (Cáceres et al., 2006). Besides, a significant difference ($P < 0.05$) in NH_4-N appeared between drum-composted RMS and materials composted in piles only (2.1 vs. 2.8 g/kg of DM; Table 3). Considering the initial levels (Table 2), DC24 and DC72 RMS lost important quantities of N through volatilization inside the drum composter. Fillingham et al. (2017a) evaluated that turned in-vessel composting for 36 h resulted in losses between 11.2 and 17.1% of TKN.

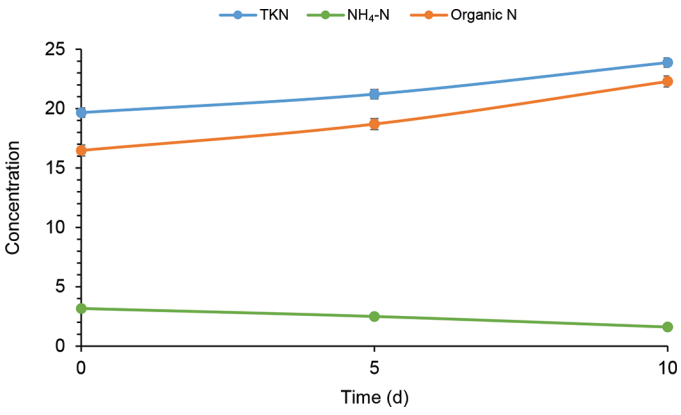

Figure 5. Mean concentration of total Kjeldahl N (TKN), NH_4-N, and organic N in recycled manure solids on d 0, 5, and 10 of the composting period. Error bars represent SE.

Bacteriological Properties. Drum-composting treatments had an effect on bacterial counts observed in RMS sampled at the input (Table 2) and the output (Table 4) of the rotating vessel, especially for *E. coli* and *Klebsiella* spp. amounts. A retention time of 24 h in the drum was enough to decrease those bacterial counts by nearly 4 and 2 $\log_{10}$, respectively (Table 4). Similar or lesser reductions were observed for the DC72 treatment for both bacteria species. Increases of approximately 2 $\log_{10}$ in *Staphylococcus* spp. concentrations were noted for DC24 and DC72 treatments, respectively. The DC72 presented better removal efficiencies for *Streptococcus* spp. and *Enterococcus* spp. (approximately 1 $\log_{10}$) than DC24 (nearly 0 $\log_{10}$).

Bacterial counts reported in previous studies are variable (Table 1), and separation and composting conditions are rarely presented. Therefore, it is difficult to explain the data published by Husfeldt et al. (2012) that present approximately 2 $\log_{10}$ less *Staphylococcus* spp. and *Streptococcus* spp. numbers in drum-composted RMS, respectively. The difference could have been

Table 4. Bacterial counts ($\log_{10}$ cfu/g of DM) in recycled manure solids after drum composting and after a 10-d composting period in pipes for each tested composting method: static windrow (SW), turned windrow (TW), drum composter for 24 h (DC24), and drum composter for 72 h (DC72)

Item	SW	TW	DC24	DC72
After drum composting				
Escherichia coli	NA[1]	NA	1.31	1.29
Klebsiella spp.	NA	NA	2.58	3.49
Staphylococcus spp.	NA	NA	8.43	7.86
Streptococcus spp.	NA	NA	6.20	4.88
Enterococcus spp.	NA	NA	5.90	5.06
After 10 d composting in pipes				
E. coli	1.97	1.33	1.29	1.90
Klebsiella spp.	3.64	4.07	2.56	5.07
Staphylococcus spp.	5.69	5.84	5.72	6.09
Streptococcus spp.	5.74	4.77	5.44	6.65
Enterococcus spp.	4.64	4.37	4.94	3.58

[1]NA = not applicable.

influenced by the fact that samples from Husfeldt et al. (2012) were frozen before culture analyses or by temperatures reached in drum composters. That could also explain the discrepancy between *Klebsiella* spp., *Staphylococcus* spp., and *Streptococcus* spp. counts of the present study and those from Harrison et al. (2008).

The 10-d composting experiment in pipes showed that treatment efficiency to reduce bacterial counts was species-dependent (Figure 6). The DC72 showed the greatest sanitization effect on *Enterococcus* spp. amounts, but increased concentrations of *E. coli*, *Klebsiella* spp., and *Streptococcus* spp. (Table 4). The DC72 was the only treatment during which multiplication of studied pathogenic agents was observed during the 10-d period.

Composting in a drum for 24 h reduced *E. coli* and *Klebsiella* spp. (Table 4), but concentrations stayed unchanged in the pipes during the 10-d period (Figure 6). No supplemental reduction was observed in DC72 samples. There is therefore no benefit to keep a drum running for 72 h instead of 24 h according to data from the present study. Besides, keeping static piles of drum-composted RMS for 5 d seems to be a better option than 10 d for DC72 because *Klebsiella* spp. and *Streptococcus* spp. counts increased from d 5 to 10 in DC72 pipes. *Klebsiella* spp. multiplied in all treatments between d 5 and d 10, except in DC24 composted RMS. Because *Klebsiella* spp. is one of the most important causes of severe clinical mastitis and is reported to induce important milk losses and cow mortality (Munoz et al., 2007), composting in windrows should also last less than 5 d to avoid contamination risks. Nevertheless, *Klebsiella* spp. levels reached at the end of the experiment were within the range reported by Harrison et al. (2008) and Cole (2015) in Table 1.

The TW and SW treatments showed similar bacterial reductions for the studied microorganisms (Table 4). No correlation was established between temperature measured in TW pipes throughout the experiment (Figure 7) and microbial concentrations.

Compost Temperature

Time-temperature profiles recorded during the experiment in pipes followed similar patterns to other investigations reporting the composting of dewatered livestock slurries (Cáceres et al., 2006; Brito et al., 2008; Brito et al., 2012). In general, the windrow composting process begins with a mesophilic phase lasting 1 to 3 d, during which mesophilic bacteria and fungi degrade noncomplex compounds such as sugars, AA, and proteins (Larney et al., 2006; Bernal et al., 2009). Figure 7 shows the breakdown of the readily available OM and N compounds, whereas the temperature of all composting piles in both halves of all composting piles increased quickly during the first 48 h.

Between d 3 and 10, RMS entered a thermophilic phase (>40°C), during which thermophilic microorganisms degrade fats, cellulose, hemicellulose, and some lignin (Larney et al., 2006; Bernal et al., 2009). In the bottom section of the pipes, the temperature reached similar levels (40–50°C) for all composted RMS ($P > 0.05$). However, in the top section, TW responded differently ($P < 0.01$) compared with the other treatments. The SW, DC24, and DC72 top sections reached approximately 60°C and stayed unchanged until the end of the experiment, whereas temperature of TW top section varied between 35 and 45°C during the last 7 d.

According to us, turning RMS daily for the TW treatment cooled the material and was too frequent to allow heat to build-up within such a small pile. This is in line with Larney et al. (2006), who indicated that temperature drops to near ambient immediately after each turning event during composting and the amount

of heat produced depends on the size of the windrow. Although turning the composted product every day is a recommended practice, turning the mix every 3 or 4 d could have been more favorable to achieve higher temperatures (Keener, 2011). Cáceres et al. (2006) also concluded that turning RMS delayed somewhat the composting process with temperature gradually increasing but to levels lower than those attained by static piles.

Air Temperature, Relative Humidity, Airflow, and Gas Emissions

Ambient air conditions were similar between experimental rooms ($P > 0.05$). Average air temperature (22.7–23.3°C) varied around the set point of 23°C for all treatments. Relative humidity inside the 12 rooms was also kept within the same range (47–67%) throughout the 10-d period. To control heat and gas accumulation

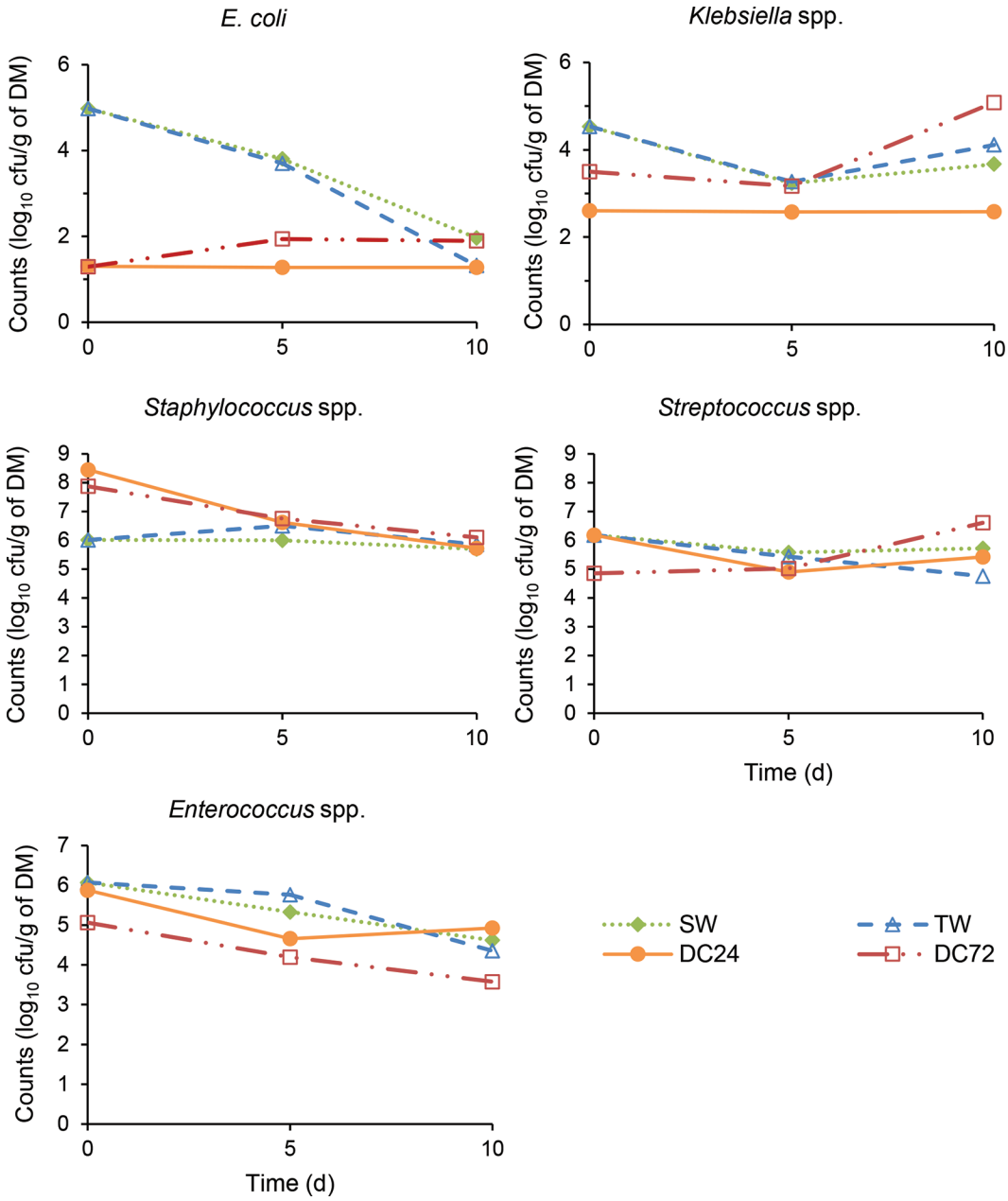

Figure 6. Mean bacterial counts in recycled manure solids on d 0, 5, and 10 following different treatments: static windrow (SW), turned windrow (TW), drum composter for 24 h (DC24), or drum composter for 72 h (DC72).

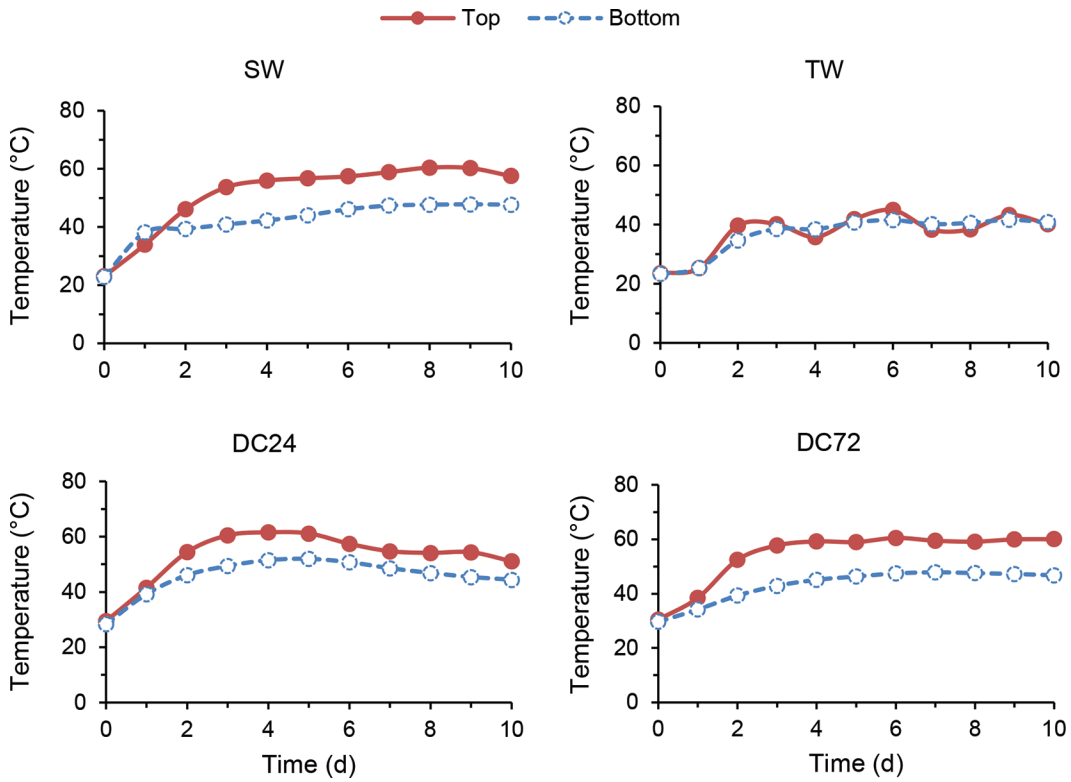

Figure 7. Daily mean temperature over 10 d in top and bottom half of recycled manure solids pipes following different treatments: static windrow (SW), turned windrow (TW), drum composter for 24 h (DC24), or drum composter for 72 h (DC72).

in the rooms, the ventilation system delivered between 3.7 and 4.0 m^3/h of fresh air.

Gaseous emissions varied ($P < 0.05$) through the pile-composting period (Figure 8). For all treatments, NH_3, CO_2, and NO_2 levels peaked in 2 or 3 d, declining gradually afterward to reach a plateau (1 mg of NH_3/min, 500 mg of CO_2/min, and 0.1 mg of N_2O/min). No N_2O values were recorded on d 9 because the high ambient temperature in the mobile laboratory disrupted the GC analyzer, which could not read such low concentrations. Methane emissions were generally around 10 mg of CH_4/min. However, some peaks were noted for the DC24 (d 2–7), SW (d 7–9), and TW (d 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, whereas anaerobic pockets are likely to appear and promote the formation of CH_4 (Cole, 2015; Pardo et al., 2015).

Despite the observed emission variations through time, no significant difference was observed between the composting approaches ($P > 0.05$). Yet, pile turning should have increased NH_3 emissions as sufficient oxygen supply ensures the decomposition process (Brito et al., 2008; Chen et al., 2015; Pardo et al., 2015). Daily turning was probably too frequent to trigger a burst of those emissions at TW temperature (Figure 7). In fact, a mesophilic range (20–40°C) tends to prevent NH_3 volatilization (Pardo et al., 2015). However, TW composts contained the lowest N concentration in the final product (Table 3), which could indicate that N losses likely occurred under other forms.

Based on conclusions of Fillingham et al. (2017b) stipulating that active composting through a rotating drum produces low emissions of CH_4 and N_2O with elevated amounts of CO_2 and NH_3, one hypothesis was that DC24 and DC72 treatments would emit more CH_4 and N_2O and less CO_2 and NH_3 than the SW and TW treatments. Actually, the formation of solid balls within the drum, due to low DM content of RMS, handicapped the degradation process by microorganisms, which could explain why there is no significant difference between the 4 composting approaches.

Dinuccio et al. (2008), Fangueiro et al. (2008), Chen et al. (2015), and Fillingham et al. (2017b) similarly investigated gaseous emissions during composting of dairy manure solids in open vessels and static or turned

windrows at temperatures over 15°C. When reported on volume of compost treated, present NH_3 (0.50–6.49 mg/min per m^3), CO_2 (264–3,622 mg/min per m^3), CH_4 (2.99–140 mg/min per m^3), and N_2O (0.01–0.75 mg/min per m^3) emissions were comparable to the reported gaseous levels of the abovementioned studies (0.02–4.43 mg of NH_3/min per m^3, 305–2,115 mg of CO_2/min per m^3, 1.7–50.3 mg of CH_4/min per m^3, and 0.00–1.13 mg of N_2O/min per m^3).

Airborne Microbial and Dust Concentrations

At d 0, important concentrations of microbial and total dust were detected as pipes were loaded with fresh or drum composted RMS (Figure 9). However, some treatments were preferable with regard to farmers' occupational exposure during RMS handling. The SW RMS associated air showed significantly lower ($P = 0.02$) 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). The SW and TW associated bacterial concentrations were below the recommendation of 10^5 cfu/m^3 for bacteria by Dutkiewicz (1997), whereas DC24 and DC72 reached that exposure limit value. The DC72 was also characterized by the highest ($P < 0.001$) airborne culturable mesophilic fungi (5.6×10^4 cfu/m^3 of air), and the highest ($P < 0.001$) total dust concentration (0.137 mg/m^3 of air). The Canadian Center for Occupational Health and Safety threshold limit value (**TLV**) – time-weighted average of 10 mg/m^3 of air for total dust was never attained throughout the 10-d experimental period and this applied for all composting processes.

Following 5 d of composting in pipes, concentrations of all studied microorganisms and dust decreased ($P < 0.001$) as airborne particles settled down (Figure 8).

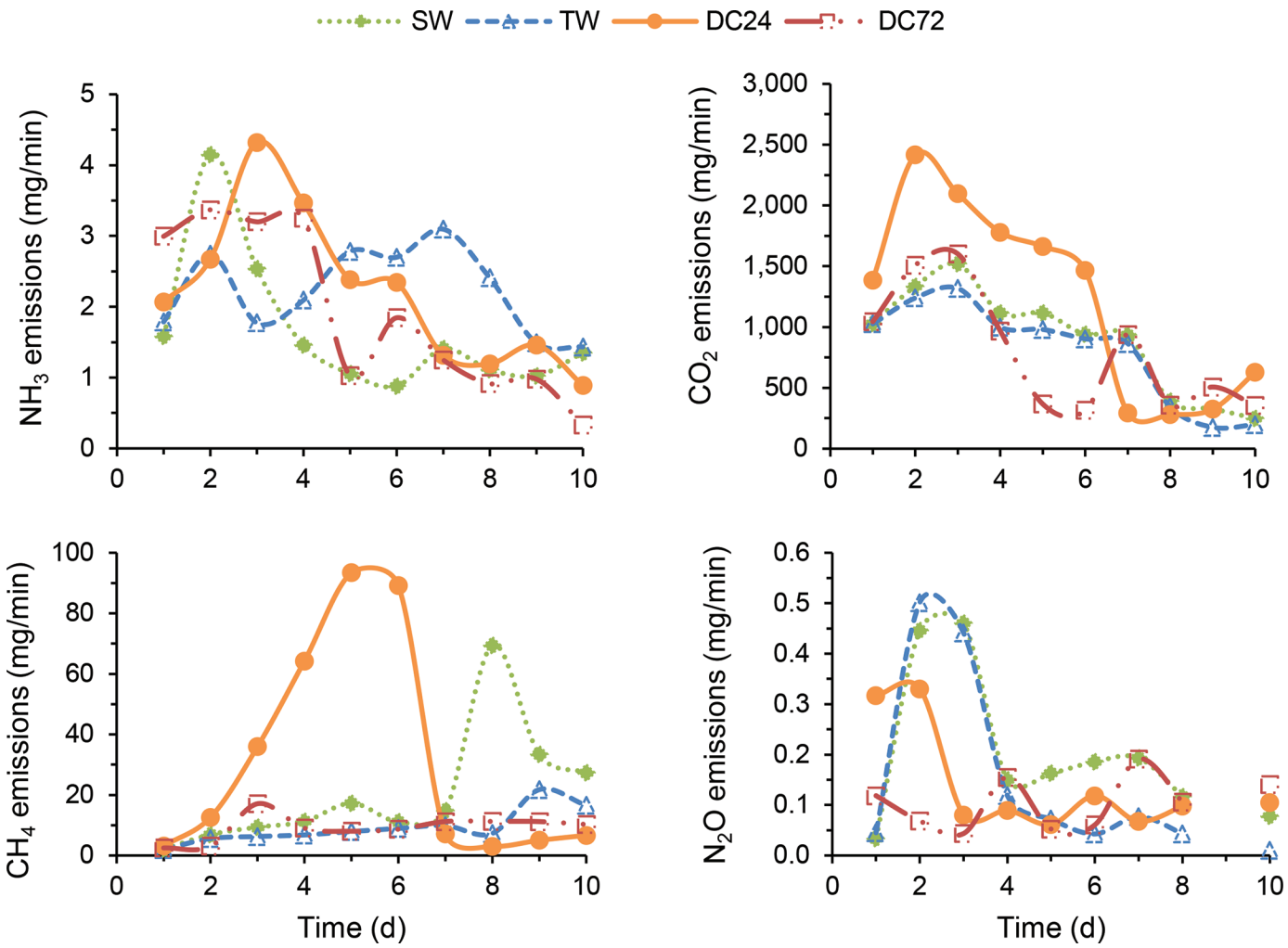

Figure 8. Daily mean emissions of NH_3, CO_2, CH_4, and N_2O over 10 d in rooms containing recycled manure solids following different treatments: static windrow (SW), turned windrow (TW), drum composter for 24 h (DC24), or drum composter for 72 h (DC72).

However, SW still showed lower ($P = 0.02$) 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). The DC72 reached one of the recommended TLV of 10^3 cfu/m^3 for bacteria (Marchand et al., 1995). Concentrations of culturable mesophilic fungi were higher ($P < 0.05$) in DC24 and DC72 experimental rooms (6.9×10^2 and 1.2×10^3 cfu/m^3 of air, respectively) than in those of SW and TW treatments (3.3×10^2 and 3.0×10^2 cfu/m^3 of air, respectively). Total dust concentrations were

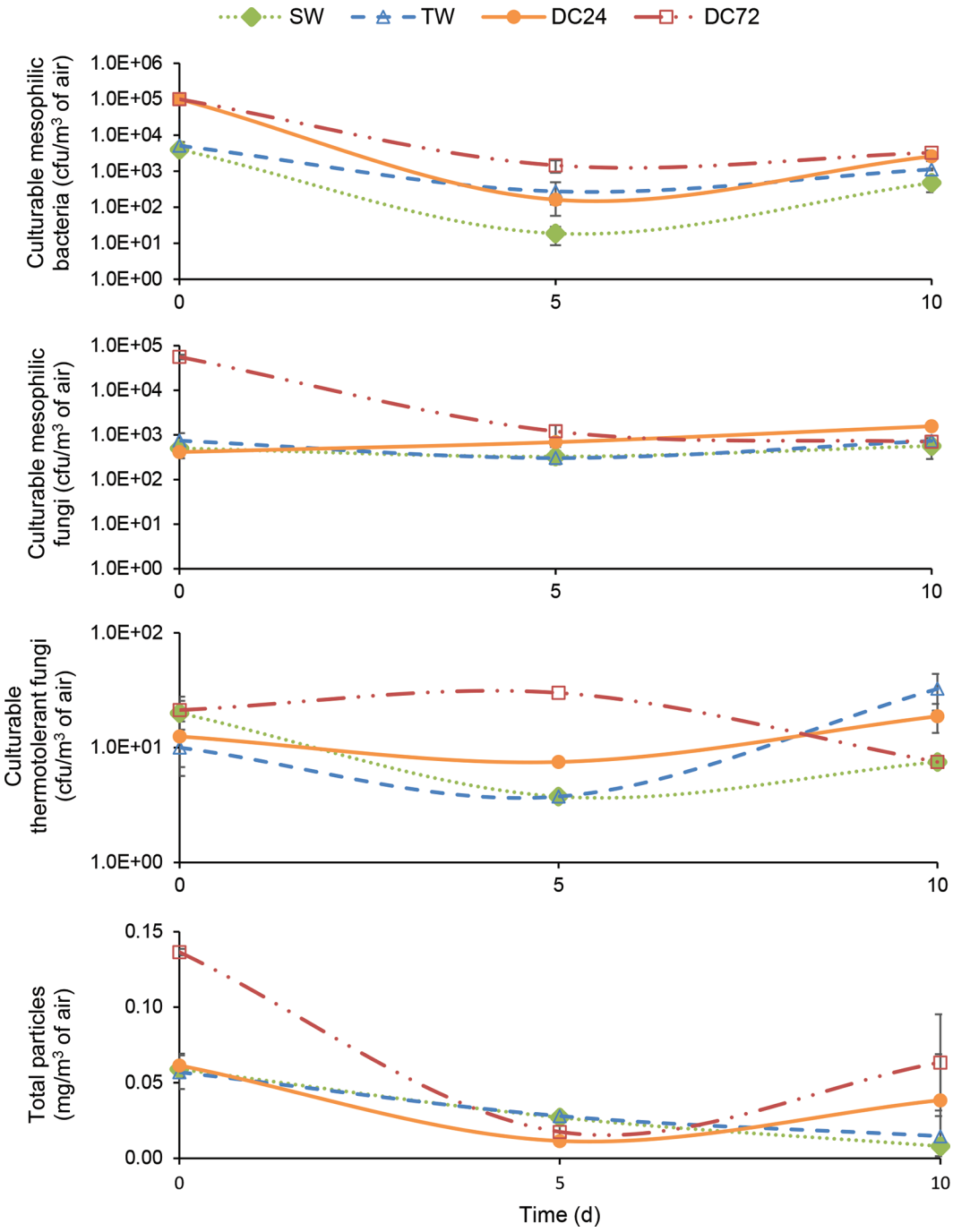

Figure 9. Culturable mesophilic bacteria, culturable mesophilic fungi, culturable thermotolerant fungi, and total dust over 10 d in experimental rooms containing recycled manure solids following different treatments: static windrow (SW), turned windrow (TW), drum composter for 24 h (DC24), or drum composter for 72 h (DC72). Error bars represent SD.

more important ($P < 0.04$) 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). Neither the culturable mesophilic fungi nor the total dust concentrations were at any time higher than the suggested TLV (Dutkiewicz, 1997) for any of the investigated treatments.

Ten days after pipe loading with RMS, DC72 treatment still showed higher ($P = 0.02$) 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 8). The SW treatment was below the recommended TLV of 10^3 cfu/m^3 of air for bacteria (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 ($P < 0.04$) than concentrations for SW and TW (0.008 and 0.015 mg/m^3 of air, respectively). Throughout the 2-wk experiment (sampling d 0, 5, and 10), concentrations of airborne thermotolerant fungi did not differ statistically for all studied composting approaches ($P > 0.05$).

Air samples were taken during the manual turning of composted TW RMS on d 0, 5, and 10 of the experiment. Only total dust concentrations on d 10 increased significantly (Figure 10), passing from 0.015 (before) to 0.073 (during) mg/m^3 of air ($P < 0.05$).

In Table 5, composting approaches were classified as those representing the lowest or highest risk of occupational exposure for dairy farmers. Pile composting of 72 h drum-composted RMS seems to represent the highest health risk for farmers.

Analysis of Composting Approaches

The 4 composting methods in this study were tested on a small scale under controlled conditions, but they simulated typical composting environments on dairy farms in Eastern Canada. Composting in rotating or static vessels, or in piles turned with tractor-assisted equipment on a concrete pad in uninsulated, ventilated, and covered buildings are usual practices found on farms (Figure 11). Except for the DM content of fresh RMS that was outside the recommended range because of the separator used (part I; Fournel et al., 2019), laboratory conditions are considered to have replicated typical full-scale farm set-ups.

Despite evident differences in density and water absorption of materials that passed through the rotating drum (Figure 2), physico-chemical properties did not change enough between treatments during the 10-d period in piles (e.g., Table 3) to be a major decision factor. Therefore, 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.

Temperature is considered the most important indicator of the efficiency of the composting process. The optimal temperature for composting reflects a compromise between minimizing nutrient loss and maximizing the inactivation of pathogenic agents. Consequently, the desired temperature range for composting is 40 to 65°C with temperatures between 45°C and 55°C giving maximum biodegradation rates and, over 55°C, inactivating pathogens (Brito et al., 2008; Bernal et al., 2009; Keener, 2011). Each treatment reached the minimal temperature (either in the drum composter or in heaps). Reductions in bacteria would then be a better indicator of the sanitation efficiency.

The treatment of fresh RMS in a drum composter for 24 h was the fastest way to reduce *E. coli* (from 1.0×10^5 to 2.0×10^1 cfu/g of DM) and *Klebsiella* spp. (from 3.2×10^4 to 4.0×10^2 cfu/g of DM) levels. Increasing the time spent in the rotating vessel to 72 h did not result in further decreases of these microorganisms. The other treatments consisting of 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 of *Staphylococcus* spp., *Streptococcus* spp., and *Enterococcus* spp. did not show clear differences between composting approaches (Figure 6).

Heaping of drum-composted RMS did not result in any additional sanitation. Although piling allowed DC24 and DC72 treatments to reach thermophilic temperatures (Figure 7), *E. coli, Klebsiella* spp., *Streptococcus* spp., and *Enterococcus* spp. amounts for DC24 were not really affected, whereas, with the exception of *Enterococcus* spp., they were slightly increased in DC72 piles (Figure 6). The static composting of DC24 and DC72 did not reveal any issue regarding gas emissions compared with SW or TW. Drum-composted RMS may therefore be stored some days before being used as bedding (Figure 8). The composting in pipes only demonstrated that DC24 material was fairly homogeneous as the gap between its top and bottom temperature was the smallest (Figure 7).

The air quality in SW and TW experimental rooms was, however, better than that related to treatment of drum-composted RMS. On d 0, SW and TW levels

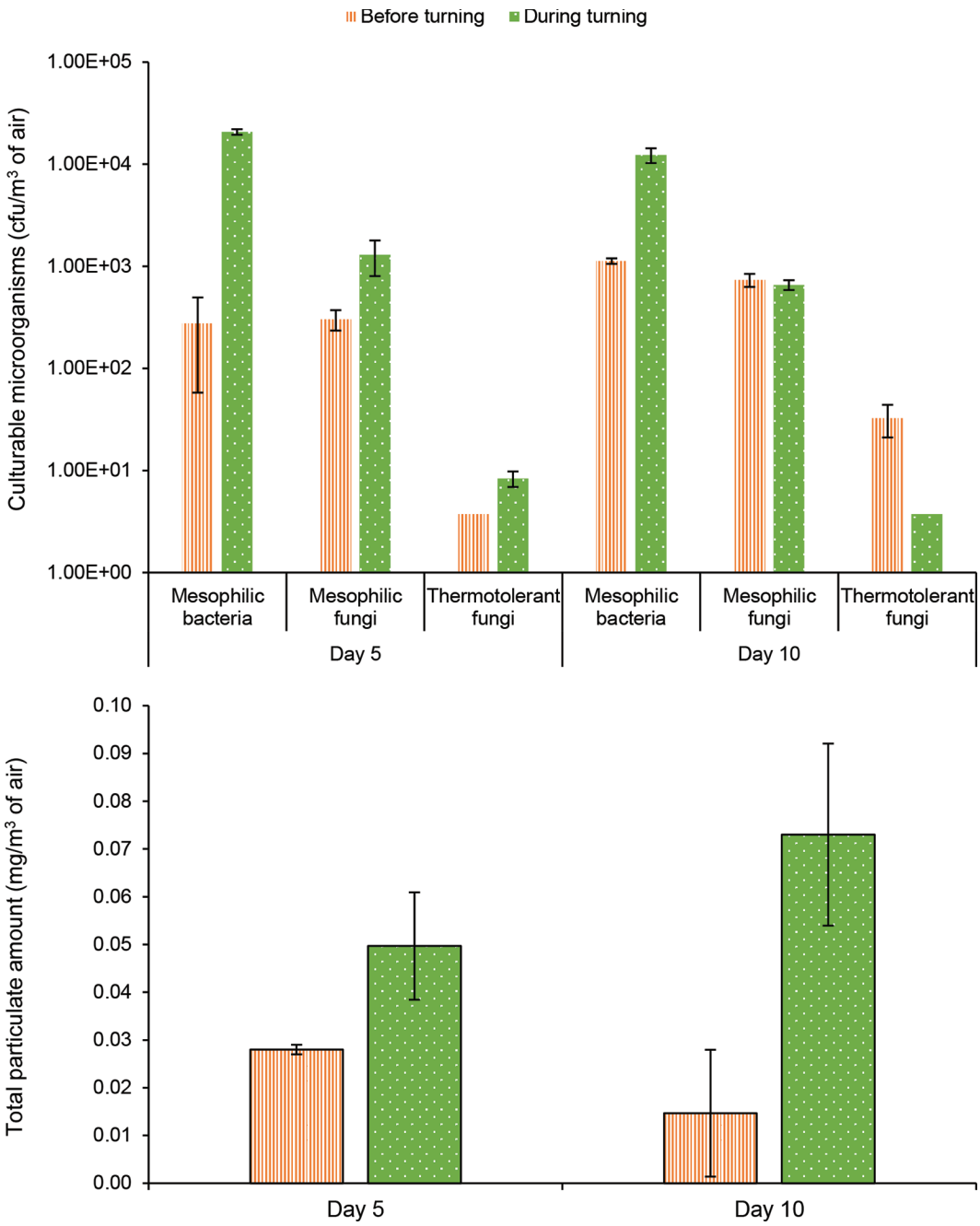

Figure 10. Effect of manual turning on airborne microbial and total dust concentrations on d 5 and 10. Error bars represent SD.

for total dust, bacteria, and fungi were generally below those observed for DC24 and DC72 treatments (Figure 9).

Finally, according to the present study, Canadian dairy farmers should be oriented toward drum composting of RMS for 24 h to rapidly achieve thermophilic temperatures, important bacterial reductions, and consistent composted RMS quality. However, further research studying milk quality and animal health on Canadian dairy farms using composted RMS are necessary to verify their suitability to be used as bedding. Composting materials can have detrimental effects on the concentration of spoilage organisms in bulk milk such as thermophilic aerobic spore-formers (Driehuis et al., 2012, 2014; Miller et al., 2015). An ongoing study from our research group on 28 Quebec dairy farms using composted RMS has not yet revealed any presence of mesophilic or thermophilic spores such as *Bacillus*

Table 5. Lowest and highest occupational risks for dairy farmers at d 0, 5, and 10 among tested composting approaches[1]: static windrow (SW), turned windrow (TW), drum composter for 24 h (DC24), and drum composter for 72 h (DC72)

	d 0		d 5		d 10	
Item	Lowest	Highest	Lowest	Highest	Lowest	Highest
Culturable mesophilic bacteria	SW	DC72	SW	DC72	SW	DC72
Culturable mesophilic fungi	TW	DC72	TW	DC72	TW	DC24
Culturable thermotolerant fungi	SW	DC72	SW	DC72	SW	DC72
Total dust	TW	DC72	DC72	SW	SW	DC72

[1]Only composting approaches representing the lowest or the highest occupational risk are included in the table.

cereus in milk from these farms (M. Gagnon, Université Laval, Québec City, QC, Canada, unpublished data). Lasting benefits of drum-composting in terms of reduced risk of intra-mammary infection are also uncertain (Valacon-Dairy, 2014) as concentrations of pathogenic agents increase rapidly once composted RMS are spread in stalls. In fact, counts in composted RMS are comparable to fresh RMS after 24 h under the cows for most bacteria (Carroll and Jasper, 1978; Harrison et al., 2008; Husfeldt et al., 2012; Cole, 2015). Another study from our group is currently looking at bacteria levels in used RMS, as well as cow welfare on RMS bedding compared with straw bedding (S. Oueslati, Université Laval, Québec City, QC, Canada, unpublished data).

CONCLUSIONS

Following solid-liquid separation, fresh RMS can be composted before being placed under dairy cows. Temperatures reached through composting increased the DM content and reduced the initial concentrations of microorganism indicators. In a humid continental climate like Canada, characterized by warm summers and frigid winters with conditions considered neither arid nor semi-arid, dairy farmers should achieve RMS as dry as possible in which particles should be submitted to uniform thermophilic temperatures to avoid animal health problems through microbial contamination. The treatment of fresh RMS in a drum composter for 24 h was the best compromise in terms of product quality, temperature reached, decreased bacterial numbers, and emitted airborne contaminants. However, more evidence on benefits of composted RMS once in stalls are needed before encouraging this practice. Therefore, bacteriological characteristics of composted RMS along with milk quality and animal health and welfare features should still be monitored in a Canadian dairy barn applying the recommended separation (part I; Fournel et al., 2019) and composting (part II) systems to evaluate health risk and optimize management practices.

Figure 11. Existing composting approaches on Canadian dairy farms: rotating drum (left), recycled silage container (center), and pile on a concrete pad (right).

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