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Ammonia emissions from liquid manure storages are affected by anaerobic digestion and solid-liquid separation

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ABSTRACT

The effects of manure management practices on ammonia (NH_3) emissions were evaluated using a micrometeorological technique at four contrasting dairy storage facilities: untreated raw manure slurry (RM), solid-liquid separation with storage of separated liquids (SL), anaerobic digestion of manure and off-farm materials (AD), and anaerobic digestion with solid-liquid separation and storage of the liquid fraction (ADL). Annual average NH_3 emissions per surface area were lowest for RM (2.7 $g\,m^{-2}\,d^{-1}$), followed by SL (4.5 $g\,m^{-2}\,d^{-1}$), AD (10.0 $g\,m^{-2}\,d^{-1}$), and ADL (15.5 $g\,m^{-2}\,d^{-1}$). Lower NH_3 emissions from the RM storage were partly due to the 30 cm thick surface crust which formed on the storage surface in summer (wood shavings was used as bedding). Greater surface crusting at the AD storage compared to the ADL storage was also likely the reason for higher emissions at the ADL storage. Relationships between NH_3 emissions, temperature, and wind-speed were observed at all sites but were strongest at sites with minimal crusting (SL, ADL) and weak at the RM storage with a crust cover. Total NH_3 emissions from each storage facility ($kg\,y^{-1}$) did not simply track the differences in fluxes; rather, facilities with greater storage (RM, AD, ADL) had higher emissions than the facility with less storage (SL) due to removal of solids and more frequent field application. Overall, bedding material, manure processing, and storage management all have important effects on NH_3 emissions from manure storage.

1. Introduction

Agriculture is the largest source of anthropogenic ammonia (NH_3) emissions in Canada and livestock and fertilizer account for over 90% (Carew, 2010). Ammonia is a toxic gas that contributes to poor air quality and environmental degradation. Atmospheric ammonia leads to the formation of fine particulates that contribute to respiratory and cardiovascular diseases (Bittman and Mikkelsen, 2009). In the United States, health costs associated with NH_3 emissions were estimated to be 36 billion in 2006 (Paulot and Jacob, 2013). In Canada, NH_3 is the only gaseous pollutant which has increased in recent years. NH_3 emissions in 2014 were 21% higher than in 1990 mainly due to increased agricultural fertilizer use and larger livestock populations (Environment and Climate Change Canada, 2016). Ammonia emissions from manure storage and land application reduce the fertilizer value of manure, which is detrimental for farm efficiency (Sommer et al., 2006).

Strategies of NH_3 emission reduction are needed to meet international agreements including the Gothenburg Protocol (UNECE, 1999). Furthermore, management practices that mitigate greenhouse gas emissions must take into account the impact on NH_3 emissions to avoid pollution-swapping. Studies suggest that manure management practices including anaerobic digestion (AD), solid-liquid separation (SLS) and AD combined with SLS could be effective to mitigate greenhouse gas emissions and provide extra economic benefits to farmers, but these technologies could increase NH_3 emissions from storage (Aguerre et al., 2012; VanderZaag et al., 2015; Holly et al., 2017).

Anaerobic digestion of manure produces renewable energy from biogas and reduces methane emissions during digestate storage. Digestion also improves the nutrient availability in digestate (Karim et al., 2005). However, anaerobic digestion alone is not a viable mitigation strategy for NH_3 emissions. Digestate has high levels of ammoniacal nitrogen ($TAN = NH_3 + NH_4{}^{+}$) and a higher pH than raw

Abbreviations: NH_3, ammonia; AD, anaerobic digestion; ADL, anaerobically digested liquid fraction; RM, manure slurry; SL, separated liquid

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Table 1
Summary characteristics of each farm, manure processing system, and storage. Where applicable, values are mean ± SD.

Parameters	RM	SL	AD	ADL
Housing type	Free stall	Free stall	Tie Stall	Free stall
Bedding	wood shavings	separated solids	Straw	separated solids
Number of lactating cows	408 ± 8	146 ± 6	117 ± 3	143 ± 7
Number of other animals	≈316	≈100	≈135	≈114
Milking system and frequency	Parlour, 3× per day.	Robots, 2.5× per day	Pipeline, 2× per day	Robots, 2.5× per day
Milk production, L $head^{-1}$ d^{-1}	35 ± 1	34 ± 2	35 ± 2	28 ± 1
Fat-Protein Corrected Milk, kg $head^{-1}$ d^{-1}	34 ± 1	34 ± 2	34 ± 2	28 ± 1
Days in Milk	182 ± 4	177 ± 9	171 ± 5	200 ± 14
MUN mg dL^{-1}	14.3 ± 1.8	13.5 ± 2.1	11.3 ± 1.2	13.3 ± 3.2
Storage type	Earthen	Tank	Earthen	Tank (measured) Earthen (estimated)
Slurry type	Slurry	Liquid fraction	Digested	Digested liquid fraction
Source surface area (SA), m^2	6,665	1,571	4,140	Tank: 707 Earthen: 2,257
Crust present	Thick	Little/None	Little	Little/None
Storage volume, m^3	24,230	3,910	10,090	Tank: 2,600 Earthen: 4,020
SA:Volume	0.27	0.40	0.41	Tank: 0.27 Earthen: 0.56
Storage completely emptied	Spring and fall	Spring and fall	Fall	Spring and fall
Digester(s) volume, m^3	N/A[a]	N/A	1,000	2,204
Generator capacity, kW	N/A	N/A	370	250
Biogas produced, m^3 d^{-1}	N/A	N/A	3,260	3,840
Measuring periods (mm/yy)	08/15–10/16	06/13–12/14	05/13–11/14	06/14–04/15

[a] Not applicable.

manure (Fillingham et al., 2017a) resulting in higher NH_3 emissions compared to untreated manure (VanderZaag et al., 2015). Holly et al. (2017) found NH_3 emissions increased by 81% from digested storage compared to untreated manure storage in a pilot-scale study.

Solid-liquid separation is an effective method of manure treatment to remove particulate organic matter from the liquid portion of the manure. This technology reduces GHG emissions, provides additional space for liquid fraction storage and produces bedding for animals from the solids fraction. Combining anaerobic digestion and solid separation is expected to increase TAN and pH, and limit the formation of surface crusts, thereby increasing NH_3 emissions during storage (Aguerre et al., 2012; VanderZaag et al., 2015). A number of studies showed that the floating natural crusts on liquid manure reduce NH_3 emissions. On the other hand, crusts increase N_2O emissions (VanderZaag et al., 2008; VanderZaag et al., 2009; Nielsen et al., 2010), but the overall contribution is small (Le Riche et al., 2016). Averaged over 6 types of dairy manure, the CO_2-equivalent contribution of N_2O emissions was the same as indirect NH_3 emissions, each being 2.0% of the GHG budget (whereas CH_4 was 96%; Le Riche et al. 2016).

Despite the growing use of these technologies for manure treatment at farm-scale, only few studies at pilot or lab-scale have focused on NH_3 losses, especially from AD and ADL storage. It is extremely difficult to create realistic conditions in the laboratory that represent on-farm storages including continuous manure loading, surface crusting, solar radiation, and wind speed. Results from these studies vary from no impact of AD (Amon et al., 2006) to significant higher NH_3 emissions from AD storage than those from the storage of untreated manure slurry (RM) (Clemens et al., 2006; Neerackal et al., 2015; Holly et al., 2017). Furthermore, Holly et al. (2017) found NH_3 emissions from separated AD storage was reduced by 28% compared to NH_3 emissions from unseparated AD storage. In addition, Neerackal et al. (2015) reported a 64% decrease in NH_3 emissions from the separated liquid fraction of AD compared to unseparated AD storage, and found no significant difference in NH_3 emissions between storage of RM and storage of the separated liquid fraction of RM.

The variability in results and lack of farm-scale studies highlights the importance of conducting on farm measurements to explore the effects of manure management on NH_3 emissions from storage. To date there has been no on-farm study of the impacts of AD, solid-liquid separation, and AD combined with separation on NH_3 emissions from manure storage at dairy farms. Therefore, the objective of this study was to quantify the effects of manure management practices on NH_3 emissions during storage at farm-scale.

2. Materials and methods

From June 2013 to November 2016, four storages facilities were monitored for NH_3 emissions. All storages were located at commercial dairy farms in Ontario, Canada. Each facility used a different manure management, resulting in storage of: raw manure slurry (RM), separated liquid manure (SL), anaerobically digested manure (AD), and the separated liquid fraction from anaerobically digested manure (ADL).

2.1. Farm descriptions

Three farms were located near Ottawa, Ontario (RM, SL, and AD) and the fourth farm (ADL) was located about 500 km away, near Drayton, Ontario. Two farms used earthen basins (RM, AD) and two used circular concrete tanks (SL, ADL). All of the farms used a dairy herd management service (Canwest DHI, Guelph, ON) that visited the farms approximately monthly. At each visit, data was gathered on each lactating cow and the whole herd including: the number of lactating cows, milk production, milk components, and days-in-milk. In addition, we contracted Canwest DHI to measure milk urea nitrogen (MUN) from each cow's milk, which has previously been suggested as an indicator of N use efficiency and NH_3 emissions (Powell et al., 2011).

Farm RM was composed of three free-stall naturally ventilated barns including a main barn for the milking and dry cows, and separate barns for the heifers and calves. The herd consisted of 419 ± 8 milking cows, about 114 dry and transitional cows, 240 heifers, and 200 calves. Bedding material in all barns was wood shavings. Liquid manure from cows and heifers was removed from the floor using scrapers and stored in an underfloor tank in each barn before being pumped (every 2–3 days) through an underground pipe to the center of the earthen storage. Semi-solid manure from the calf barn was dumped into the earthen storage using a tractor. Herd-average milk production was among the highest of all farms (Table 1). MUN was the highest of all farms, and in-line with the industry average of 14 mg dL^{-1} reported by