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Methane emissions from storage of digestate at a dairy manure biogas facility

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ABSTRACT

Conventional manure storages are an important source of methane (CH_4), a potent greenhouse gas. Anaerobic digestion is an alternative manure management practice potentially able to provide environmental benefits, including the reduction of CH_4 emissions from slurry storage. This study was conducted at a commercial farm in Ontario where a biodigester system became operational in May 2012. The purpose was to quantify year-round CH_4 emissions from a digestate storage tank, examine the relationship between emissions and its driving factors, and compare these results to a similar emissions dataset from untreated manure measured during one year before the biodigester became operational. A micrometeorological mass balance approach was used to measure CH_4 fluxes. Total annual CH_4 emissions from digestate were 1.0 $kg\,m^{-3}\,y^{-1}$, which was 85% lower compared to untreated manure. Monthly average volatile solids (VS) mass in the storage tank was 73 ± 24 Mg for digestate and 107 ± 30 Mg for manure, representing a 32% VS reduction in the tank, suggesting that lower emissions were not only due to VS mass reduction after biodigestion and solid-liquid separation. The annual CH_4 emissions scaled by VS were 26 $g\,kg^{-1}$ VS y^{-1} for digestate and 76 $g\,kg^{-1}$ VS y^{-1} for manure, suggesting that VS in the digestate were less suitable for CH_4 production (less digestible). This was also verified when investigating the relationship between fluxes and its driving factors: VS concentration did not correlate with CH_4 emissions per volume for digestate ($r = 0.37$; $p = 0.29$), but did for untreated manure ($r = 0.95$; $p = 0.002$). However, the correlation of temperature with emission was stronger for digestate than manure at all depths with no lag, especially at 2 m depth ($r = 0.98$, $p < 0.001$). At the same air temperature, digestate was warmer than manure, owing to the digestate leaving the digester at 38 °C. This study showed that co-digestion of dairy manure and off-farm materials (35% of loading volume) with a 60-day hydraulic retention time and subsequent solid liquid separation significantly reduced facility-scale CH_4 emissions from the storage tank.

1. Introduction

A large portion of dairy facilities use liquid manure systems (Jayasundara et al., 2016). Manure management in cold climates require storage capacity for at least 6 months in the United States (USEPA, 2001), and at least 240 d capacity is required in Ontario (OMAFRA, 2010). In storage, anaerobic digestion (AD) of degradable organic matter (OM) in the liquid manure occurs naturally, generating biogas, a mixture of methane (50–75% vol), carbon dioxide (25–50%) and trace amounts of other gases (< 1%) (Gomez, 2013). Methane (CH_4) when released to the atmosphere, however, is a serious environmental problem due to its global warming potential which is 28× greater than carbon dioxide (CO_2) (Myhre et al., 2013). CH_4 emissions typically comprise > 95% of greenhouse gases (GHG) emissions from liquid manure storages (Amon et al., 2006). In Canada, manure management accounted for 14% of agriculture's GHG emissions in 2014 (Environment and Climate Change Canada, 2016). A comprehensive review of field-based studies measuring GHG emissions from dairy manure (Owen and Silver, 2015) highlighted opportunities for GHG emission reduction from conventional liquid manure systems, while stressing the need for both field scale and long-term studies to provide more accurate emission reduction opportunities.

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Use of liquid manure to generate biogas has long been suggested as a potential GHG mitigation practice (Wang, 2014). In a farm biodigester system, manure is placed in a covered tank (biodigester) to stabilize and optimize biogas production. The efficiency of biogas production depends on the absence of oxygen (anaerobic conditions), uniform temperatures, optimum nutrient supply and pH (Gomez, 2013). Farm AD systems regularly adopt a single-step process in the mesophilic temperature range (32–42 °C) with wet fermentation (dry matter < 20%) and quasi-continuous feeding (Gomez, 2013). The degradable organic matter content is often increased with the addition of co-substrates such as food waste and by-products of food processing along with manure. Combined heat and power systems use the biogas to generate electricity and heat, potentially replacing energy from fossil fuels. The treated effluent (digestate) is pumped (frequently after solid/liquid separation) to an open storage tank, similar to untreated manure storage in conventional practice, to be used later as organic fertilizer. This system is an alternative option to manure management that can provide multiple environmental benefits (Artrip et al., 2013).

It has been suggested that CH_4 emissions from digestate storage are substantially lower compared to untreated manure, because part of the degradable matter (volatile solids) is consumed inside the biodigester, followed by a further decrease after solid separation (Amon et al., 2006). However, there are other factors that might stimulate enhanced CH_4 production after digestion. Substrate temperature plays a major role in controlling CH_4 emissions in manure storages (Clemens et al., 2006; Sommer et al., 2007; Daniel-Gromke et al., 2015) and the digestate temperature can be substantially higher than the air temperature (Liebetrau et al., 2013). Liebetrau et al. (2013) determined the digestate storage tank was the major potential source of CH_4 emissions, followed by CH_4 slips from gas utilization in 10 biogas plants in Germany. Daniel-Gromke et al. (2015) found that the residual gas potential of digestate was > 10% in 10 of 12 biogas plants investigated (range 4–23%). Baldé et al. (2016b) found significant CH_4 emissions from a biogas plant where annual cumulative emissions from digestate represented 12% of the CH_4 produced within the digester. Quantifying emissions from digestate in storage is also important to determine opportunities in energy production and biogas plant efficiency increases by, for example, recovering CH_4 from digestate.

Few studies have quantified the avoidance of CH_4 emissions associated with the storage of digestate compared to untreated manure (Amon et al., 2006; Clemens et al., 2006; Rodhe et al., 2015). Most studies have shown that AD has the potential to reduce GHG emissions (Amon et al., 2006; Owen and Silver, 2015). However, pilot-scale studies have shown contradictory results. Amon et al. (2006) concluded that AD was effective in reducing CH_4 emissions from the storage phase, as digestate had lower emissions than untreated stored manure over 80 d. In contrast, Rodhe et al. (2015) found that daily mean CH_4 emissions over 3 summer months were significantly higher for digestate (~3× higher on a per unit volume basis) than untreated manure. These studies highlight the need for further investigation to determine the CH_4 emission reduction over a range of conditions.

Hrad et al. (2015) emphasized the importance of long-term field studies to capture meteorological changes as well as operational activities in biogas plants. Liebetrau et al. (2013) found that CH_4 losses from digestate for two 1-week measurement periods on each of 10 plants using a floating chamber were ~50% higher in the summer than winter for biodigesters fed with a mixture of manure and crops. Rodhe et al. (2015) found negligible emissions from digestate in the winter. These observations highlight the need for year-round measurements to determine the annual CH_4 emissions of digestate. In the only year-round study at a commercial farm biodigester, Baldé et al. (2016b) used open-path sensors and a backward Lagrangian Stochastic (bLS) model to measure CH_4 emissions from digestate. Methods such as bLS and micrometeorological mass balance (MMB) are well-suited for year-round monitoring (Harper et al., 2011). The MMB is particularly adapted for year-round flux measurements of sources such as manure/digestate tanks, since it is suitable for a broad wind direction range and there are no assumptions regarding the nature of turbulent flow (Wagner-Riddle et al., 2006; VanderZaag et al., 2011). There is a need for long-term facility-scale studies comparing untreated manure versus digestate to better understand the driving forces, and quantify the real-world emission reduction potential of AD.

In this study, CH_4 emissions from a digestate open storage tank on a commercial dairy farm were measured using the micrometeorological mass balance method for one year and then compared to one year-round manure emission data from a complementary study (Kariyapperuma et al., 2017) using a similar experimental set up at the same site before the biodigester became operational. Environmental conditions and digestate characteristics were also determined to allow establishment of the emission drivers and their relationships with emissions. The uniqueness of this study consisted in comparing digestate CH_4 emissions with those from untreated manure at the same farm before the biodigester became operational, so that important field variables related to manure production (animal breed, animal feed) remained similar for both scenarios.

The objectives of this study were to (i) quantify year-round field CH_4 emissions from AD digestate; (ii) examine the relationship between emissions and emissions drivers (volatile solids and temperature); and (iii) compare CH_4 emissions between untreated manure and digestate at the same farm.

2. Materials and methods

2.1. Site description

The study was conducted at a commercial dairy farm near Alma, Ontario, Canada, (43°45′N 80°40′W, elevation 400 m) from Jan 1 to Dec 31, 2013. This area of Ontario has relatively high elevation and is comparatively cool compared to other parts of Southern Ontario. The farm had Holstein cows divided into four main barns according to animal category (Fig. 1). There were about 140 lactating cows, 25 transition and dry cows, 65 heifers in a side bank barn and 15 calves in a small calf nursery located at the farm entrance. Additional replacement animals were kept at another farm. Solids separated from the digestate were used as bedding material. Cow feeding consisted of a mixture of corn silage, alfalfa-grass silage, grass hay, straw, high moisture corn, and custom supplement (Ngwabie et al., 2014). Wash-water from milking robots was stored separately from manure and did not pass through the digester.

Manure was scraped from the two main barn slatted floors (with lactating and dry cows) and temporarily stored in covered tanks under the barns with the capacity of about 3000 m^3 to hold manure prior to digestion: 4 rectangular tanks under the dry cow barn (two 13 × 8 m, with 2.4 m depth; two 13 × 12 m, with 2.4 m depth), one tank (27 × 8 m, 3 m depth) under the transition cow barn, one tank (42 × 8 m, 3 m depth) under the milking cow barn and a manure runoff tank (6.3 × 6.3 m, 2.6 m depth). From the under-barn storages, manure was pumped directly into the biodigester or into a mixing tank where it was mixed with co-substrates before being pumped into the biodigester. There was an off-farm material storage tank (100 m^3) to receive co-substrates to be used as feeding for the biodigesters and a small tank (0.5 m^3 working volume) where the biodigester input mixture was pasteurized (Fig. 1). Manure from the calf nursery and bank barn is not added to the anaerobic digesters or digestate storage.

The biodigester system was composed of two-stage continuous stirred-tank reactors that included two identical circular tanks (14.63 m diameter; 7.3 m depth, working volume 1102 m^3) connected in series. The total hydraulic retention time (HRT) was 60 d and the operational temperature was kept around 38 °C (mesophilic digestion). The biodigesters had a rubber roof with a pressure control valve to safely retain the biogas produced. A pipeline directed the biogas to a 250 kW electrical cogeneration unit and a flare, used in case of excess biogas flow.