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REVIEW

# Nitrous oxide production from cattle and swine manure

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**Abstract** The aim of this review is to summarize the current knowledge of nitrous oxide ($N_2O$) production from manure. The article investigates the scientific literature regarding $N_2O$ emissions according to different factors, such as microclimate, season, manure composition, microbial population, management, storage conditions, and type of digestion. Nitrous oxide is formed through the microbiological processes of nitrification and denitrification. The amount of $N_2O$ produced from manure storage depends on type of manure management. The anaerobically stored farm yard manure (FYM) emitted more $N_2O$ emissions than the composted FYM. The anaerobic storage of liquid manure reduces $N_2O$ production. Covering the slurry store (SLR) with a chopped straw increased $N_2O$ emissions. Finally, emission factors from manure treatment and management are listed in table.

**Keywords:** nitrous oxide, manure, slurry, housing

## Introduction

Contemporary agriculture is characterized by the intensive production of livestock in confined facilities and land application of stored waste as an organic fertilizer. Animal agriculture potentially contributes up to 50 % of total agricultural nitrous oxide ($N_2O$) emissions (Klein de and Eckard 2008). The anthropogenic greenhouse gas emission from animal manure is estimates on 20 % of $N_2O$ (Sommer and Moller 2000).

$N_2O$ emissions from nitrogen (N) excreted as animal waste alone could be as much as 30–50 % of the global agricultural $N_2O$ emissions, suggesting that the contribution of animal agriculture to total agricultural $N_2O$ emissions could be in excess of 50 % when including emissions from N fertilizer use (Oenema et al 2005; Klein and Eckard 2008). $N_2O$ emissions occur high when N fertilizers are used for production of concentrates to feed the animals, as well as from excretal returns (Davidson 2009; Petersen and Sommer 2011).

$N_2O$ is produced during several microbial processes in the nitrogen (N) cycle of terrestrial and aquatic systems. Typically, 70 % to 90 % of the N ingested by herbivores is excreted, either during grazing or via application of manure collected outside grazing periods (Schils et al 2013). Housed animals excrete as dung and urine according to Paustian et al (2004) 80 to 95 % of the N in their diet, and some proportion of this N is emitted as $N_2O$ during collection, storage, and application. Ruminants excrete between 75 and 95 % of the N they ingest, with excess dietary N increasingly excreted in the urine, while dung N excretion remains relatively constant (Castillo et al 2000; Eckard et al 2007).

In animal husbandry, $N_2O$ emissions are associated with manure management and the application and deposition of manure in crop or pasture land. Manure treatment can be an important source of $N_2O$ emissions, accounting for an estimated 5 % of global $N_2O$ emissions (Owen and Silver 2015). Major agricultural manure emission sources are reported to be $N_2O$ from poultry sheds and from beef feedlots (Pratt et al 2014).

Collected manure may be handled in solid (farmyard manure, deep litter) or liquid form (slurry with typically 1 % to 10 % of dry matter) (Schils et al 2013). Dung and urine are often separated to solid stacked manure and slurry (SLR), with or without subsequent composting of the stacked manure and (anaerobic or aerobic) treatment of the SLR. In other production systems, effluent from barns is transferred into open anaerobic ponds (lagoons) where the effluent is typically stored for many months, with the potential of generating large quantities of emissions (McGahan et al 2016).

$N_2O$ is released from excrement and urine excreta, from SLR applied for crop or pasture production, and aerobic and anaerobic degradation of livestock waste in the lagoons and dry manure pile (Saggar et al 2004; Fabbri et al 2007; Borhan et al 2011; Redding et al 2015).

## Formation $N_2O$

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The various pathways of $N_2O$ formation could describe for apply to the manure environment, but the potential for $N_2O$ emissions will depend on manure management practice. Manure contains most elements necessary for stimulating soil nitrification and denitrification processes that form $N_2O$. These processes are transient, depending on the amount and form of available N ($NH_4^+$ or $NO_3^-$), soil oxidation–reduction potential, degradable carbon (C) sources, soil temperature, water content, and microbial population (Montes et al., 2013). Poor correlations between $N_2O$ efflux and soil physicochemical variables and fertilizer loading rate point to the complexity of interacting factors affecting $N_2O$ production and emission (Whalen 2000).

The main sources of $N_2O$ from agriculture are nitrification and denitrification processes in soil. Farms primarily emit $N_2O$ arising mainly from nitrogen fertilizer (organic manures or inorganic fertilizers) application to soil, direct N deposition by grazing animals, or manure storages (Whalen et al 2000; Crosson et al 2011; Adler et al 2015). Nitrous oxide can also be produced indirectly when manure N is lost through volatilization as $NH_3$, NO, and $N_2O$ and is nitrified and denitrified in soil following redeposition (Montes et al 2013). The smaller contributions from barn floors, where both aerobic and anaerobic conditions can exist (Chianese et al 2009; Van Middelaar et al 2013; Eckard et al 2003).

The major $N_2O$ contributor is normally the denitrification process under anaerobic conditions, but nitrification under aerobic conditions may also contribute. Nitrification and denitrification rates are affected by numerous soil and climatic or seasonal factors (Monaghan and Barraclough 1993; Chadwick et al 2000; de Klein and Eckard 2008). The rate of formation and emission of $N_2O$ varies through time with changes in the porosity, moisture content, temperature, amount of solids in the manure, and N or dietary protein content of the soil or manure substrate (Külling et al 2001; Kebreab et al 2006; Chianese et al 2009; Li et al 2014). Anaerobically stored solid manure emitted much more $N_2O$ than the compost (Amon et al 1998a). Chadwick et al (2000) also reported that immediate emissions of $N_2O$ from the beef manure was likely due to rapid nitrification of ammonium or denitrification of nitrate already in the manure.

Most of the $N_2O$ resulting from manure is produced in manure-amended soils through microbial nitrification under aerobic conditions and partial denitrification under anaerobic conditions, with denitrification generally producing the larger quantity of $N_2O$ (Montes et al 2013). Nitrogen in liquid manure is mostly in the form of ammonium ($NH_4^+$) and organic N, and though anaerobic lagoons are generally anaerobic, aerobic conditions which could promote denitrification exist at inlets. Other $N_2O$ formation reactions are also possible, such as denitrification of nitrate ($NO_3^-$) (Owen and Silver 2015).

Mahimairaja et al (1995) examined the denitrification loss of N from fresh poultry and animal (dairy, sheep, pig and horse) manures, and from poultry manure during composting with different amendments. The results indicated that during denitrification, the amount of $N_2$ produced is generally greater than that of $N_2O$. The ratio of $N_2O:N_2$ varied from 0.09 to 0.21.

## Factors affecting $N_2O$ releasing

When fecal matter is excreted by animals, it undergoes a series of reactions such as decomposition, hydrolysis, nitrification, denitrification, fermentation etc., from which $N_2O$ can be produced. Based on the principles of thermodynamics and reaction kinetics, these reactions are commonly controlled by a group of environmental factors such as temperature, moisture, stacking, density, litter addition, mixing, composition, and aerobic decomposition during storage of the manure, also redox potential, pH, substrate concentration gradient, etc. (Oenema et al 2005; Yamulki 2006; Kebreab et al 2006; Li et al 2012; Rzeźnik and Mielcarek 2016). The influencing factors appeared to be also the manure removal frequency, dry matter content, and time deposit of the manure (Fournel et al 2012). After 6 weeks of storage $N_2O$ emission from farmyard manure (FYM) and deep litter manure reached a maximum (Külling et al 2002).

$N_2O$ emissions are strongly correlated with all these parameters (Mihina et al 2012; Owen and Silver 2015). This suggests that in FYM, at least a portion of the $N_2O$ fluxes were derived from denitrification, which requires the same general environmental conditions as methanogenesis (warm temperatures, abundant labile C, anaerobic conditions) (Owen and Silver 2015).

One main factor influencing the amount of $N_2O$ emissions seems to be the manure temperature. This would explain why under summer conditions the emission rates of $N_2O$ are different than under winter conditions (Jungbluth et al 2001). Sommer and Moller (2000) studied composting of pig deep litter during a 4-month period. Emissions of $N_2O$ were only significant in the low temperature phases. $N_2O$ was also produced in the center both initially and after the temperature of the compost had dropped to below 45 °C (Sommer and Moller 2000).

The initial C: N ratio and dry matter content of the stored FYM are also the most important factors affecting $N_2O$ emissions. The greater C content in the organic FYM compared with the conventional FYM corresponded to a reduction in total $N_2O$ emission (Yamulki 2006). $N_2O$ emissions increase with the N content of waste, the extent to which waste is allowed to become aerobic (allowing the initiation of nitrification-denitrification reactions) and the length of storage (Mosier et al 1998). Further, owing to interactions between available C and N sources in the correct oxidation form, semi-permeable manure storage covers can enhance $N_2O$ formation (Hansen et al 2009; Nielsen et al 2010; Gerber et al 2013).

**Table 1** N2O production and emission factors from manure storage facilities (per animal)

Cattle manure, without covering; 0.78 mg.m$^{-2}$ h$^{-1}$ (Ross et al 1999, cited by Jungbluth et al 2001).

Manure, summer, 3.5 t, winter, 7 t; anerobically stored vs. composted, 3 times per week, ODC, 74.7 g.t$^{-1}$ vs. 49.8 g.t$^{-1}$ (Amon et al 1998a).

Cattle manure (housing, storage, spreading); ODC, FTIR; yearly average 0.62 g.LU$^{-1}$.d$^{-1}$ (Amon et al 1998b, cited by Amon et al 2006a).

Dairy solid manure system; 25.8 mg.LU$^{-1}$.h$^{-1}$ (Amon et al 1999; cited by Amon et al 2006a).

Dairy liquid manure system; 25.4 mg.LU$^{-1}$.h$^{-1}$ (Amon et al 1999; cited by Amon et al 2006a).

Dairy SLR, storage, 1200 m$^3$; winter, TDL; 14 mg.m$^{-3}$.d$^{-1}$ (Hensen et al 2006).

12 Brown Swiss, 52 DIM, 637 kg LBW, 30,9 kg MY, individual stalls, slatted floor, TMR, 4 MS (DL, SLR, urine-rich SLR, FYM); 7 wks, TDL; according MS: 9.3 ng.m$^{-2}$.s$^{-1}$, 5.6 ng.m$^{-2}$.s$^{-1}$, 12.1 ng.m$^{-2}$.s$^{-1}$, 556.4 ng.m$^{-2}$.s$^{-1}$; (DL, SLR, FYM) 42 mg.d$^{-1}$, 12 mg.d$^{-1}$, 886 mg.d$^{-1}$ (Külling et al 2001).

Pig manure, without covering; from containers (0,5 m$^3$) closed for 1 h gas measurement, summer, GC; 0.67 mg.m$^{-2}$.h$^{-1}$ (Ross et al 1999, cited by Jungbluth et al 2001).

Pig manure, with straw covering; from containers (0,5 m$^3$) closed for 1 h gas measurement, summer, GC; 0.95 mg.m$^{-2}$.h$^{-1}$ (Ross et al 1999, cited by Jungbluth et al 2001).

Pig manure, without covering; winter, FMC, GC; 0.35 mg.m$^{-2}$.h$^{-1}$ (Ross et al 1999, cited by Jungbluth et al 2001).

Pig manure, with straw covering, winter, FMC, GC; 0.30 mg.m$^{-2}$.h$^{-1}$ (Ross et al 1999, cited by Jungbluth et al 2001).

160 fattening pigs, uncovered SLR vs. covered SLR; warm, FC; after 50 days, 23 g.m$^{-3}$ vs. 30 g.m$^{-3}$; after 200 days, 119 g.m$^{-3}$ vs. 114 g.m$^{-3}$ (Amon et al 2007).

160 fattening pigs, uncovered SLR, covered SLR; cold, FMC; after 50 days, 36 g.m$^{-3}$ vs. 18 g.m$^{-3}$ (Amon et al 2007).

Fattening pigs; FS housing, anaerobic effluent pond, short hydraulic retention tank; 2x30 ds; $N_2O$ from housing and pond, or below the detection limits, total emissions from the short hydraulic retention tank: winter 0.001 mg $N_2O$-N.LU$^{-1}$.d$^{-1}$, summer 5.9 mg $N_2O$-N.AU$^{-1}$.d$^{-1}$ (McGahan et al., 2016).

3 fattening pigs farms; SLR lagoons; every M, MBIGA; lagoon concentration 636.8 mg $NH_4$-N kg$^{-1}$, 201.0 mg $NH_4$-N kg$^{-1}$, 236.6 mg $NH_4$-N kg$^{-1}$, 0.3 kg $N_2O$-N ha$^{-1}$ d$^{-1}$, 0.4 kg $N_2O$-N ha$^{-1}$ d$^{-1}$, 0.0 kg $N_2O$-N ha$^{-1}$ d$^{-1}$ (Harper et al 2004).

Manure, fattening pigs, DL, stored 113 ds; every wk, RC (tent), GC; d 11: 28 mg $N_2O$-N.kg DM$^{-1}$ d$^{-1}$, after d 40: 6 mg $N_2O$-N.kg DM$^{-1}$ d$^{-1}$ (Wolter et al 2004).

The increase in manure organic matter accelerates soil metabolism, depleting oxygen, triggering denitrification and $N_2O$ emissions (Hristov et al 2013; Gerber et al 2013). On the contrary, anaerobic digestion, or separation of manure solids, lowers the organic content of manure, which generally results in lower emissions of $N_2O$ (Clemens et al 2006; Velthof and Mosquera 2011; Gerber et al 2013). Manure affects the balance between $NH_3$ and $N_2O$ emissions. This interaction may be positive (e.g., both emissions are reduced by an airtight cover during storage and stimulated by composting), or negative (e.g., direct $N_2O$ emissions from soil will potentially increase if losses of $NH_3$ are prevented during storage or field application) (Petersen and Sommer 2011). $N_2O$ release from stored manure was low when $NH_3$ was high (Külling et al 2002).

The amount of $N_2O$ produced from manure storage depends on the amount of N excreted and duration of storage (Merino et al 2011). Solid manure rich in high fiber bedding material has a high porosity that promotes aerobic fermentation, and heat, which can stimulate $N_2O$ emissions (Petersen et al 1998). Also, the higher the density the lower the emission of $N_2O$ (Oenema et al 2005). However, covering delayed aeration of the stored manure; this reduced internal heat production, degradation of organic matter, and emission of greenhouse gases and ammonia (Hansen et al 2006). At the study of Sommer and Moller (2000) was production of $N_2O$ restricted to the surface layers during the thermophilic phase of composting (Sommer and Moller 2000). Brown et al (2000) found that the mean $N_2O$-N fluxes were between 0 and 0.33 g N m$^{-2}$ d$^{-1}$, and $N_2O$ was only generated in samples from the top two layers of the dairy FYM pile. Manure samples from the 30 to 45 cm depth were adjusted by amendment with chopped straw to 70, 75, and 80 % water content. These samples produced twice as much $N_2O$-N as the unamended samples.

Slurry separation reduces emissions if losses during storage of the solid fraction can be kept on a low level (Amon et al 2006b). At the study of Hansen et al (2006), emissions of $N_2O$ from an uncovered and covered heap of solid manure separated from pig SLR were compared, and related to the oxygenation level inside the manure heap. Approximately 15 % of the initial nitrogen content of the solids separated was found to be lost when the separated solids were stored uncovered. Almost 5 % of the initial N content was found to be lost as $N_2O$. Emissions of $N_2O$ were reduced by 12 %, when the manure heap was covered with an airtight material. The oxygenation level inside heaps of solids separated from pig SLR was found to influence the production and emission of greenhouse gases during the storage period (Hansen et al 2006).

In contrast, in liquid manure lagoons particulate organic matter is a physical barrier against gas exchange when a surface crust forms (Petersen and Sommer 2011). Anaerobic digestion is in fact an effective means to reduce greenhouse gas emission (Amon et al 2006a). However, the anaerobically stored FYM emitted more $N_2O$ emissions than the composted farm yard manure (Amon et al 1998a; Amon et al 2001).

Covering the SLR store with a layer of chopped straw increased greenhouse gas emissions mainly by increasing $N_2O$ emissions. When liquid manure stored as anaerobic SLR, $N_2O$ emission is low, but $NH_3$ and $CH_4$ emissions are high, depending on the cover of the slurry and mixing rate (Oenema et al 2005). $N_2O$ emissions can occur from SLR when a dry crust is formed on the surface with combination of anaerobic and aerobic micro-sites (Philippe and Nicks 2013). Therefore, straw cover and SLR aeration showed negative environmental effects (Amon et al 2006b).

Natural surface crusts may develop into a porous matrix with high $O_2$ availability that harbors an active population of aerobic microorganisms. The occurrence of $NO_2^-$ and $NO_3^-$ in the crusts also indicate the presence of actively metabolizing $NH_3^-$ oxidizing bacteria (Nielsen et al 2010). The floating crust is important because it provides a substrate that spans anaerobic and aerobic environments, where $N_2O$ production can occurs (Petersen and Sommer 2011).

Floating crusts on manure storages are environments with intense microbial activity, and microbial processes are governed by the extent of oxic conditions that are governed by the moisture of the crust. Hansen et al (2009) study investigated whether physical properties of the crust or crust microbiology had an effect on the emission of the $N_2O$ when crust moisture was manipulated (dry, moderate, and wet). However, an increase in $N_2O$ emission was observed in all crusted treatments exposed to anoxia, and this was probably a result of denitrification based on $NO_x$ that had accumulated in the crust during oxic conditions.

## Comparison of manure types

The type of manure can be crucial factors in reducing the extent of nitrogen lost (Bell et al 2016). The amount of $N_2O$ produced from manure storage depends on type of manure management (Yamulki 2006; Merino et al 2011; Rzeźnik and Mielcarek 2014). Total manure emissions are the product of the amount of N excreted during storage multiplied by the associated emission factor for that manure management system and animal population (Crosson et al 2011).

A lower dietary protein content furthermore reduced $N_2O$ emission rates in most manure types but increased $CH_4$ emission from urine-rich SLR. In deep litter manure, characterized by the highest C: N ratio, emission rates of total N, $N_2O$ values were intermediate. Substantial emission of $N_2O$ occurred with FYM. C: N ratio of manure was shown to be suitable to predict total N loss during storage in all manure types whereas urine N proportion and manure pH were only of use with liquid manures (Külling et al 2002).

Amon et al. (1998b) compared $N_2O$ emission in solid and liquid manure management systems. In the tie-stall housing of dairy cows no differences were found between a SLR based and a straw based system. Only deep litter systems with straw showed higher $N_2O$ emissions. This reflected the higher microbial biomass content and approximately neutral pH at FYM field (Mogge et al 1999).

$N_2O$ synthesis needs close combination of aerobic and anaerobic areas. These heterogeneous conditions are not met within SLR but deep litter (Philippe and Nicks 2013). Therefore, for waste of a given N content, anaerobic lagoons will result in the least $N_2O$ emissions whereas solid storage and dry-lot handling will promote emissions (Paustian et al 2004). The anaerobic nature of liquid manure systems reduces $N_2O$ production (Kebreab et al 2006).

Majority of swine production systems use anaerobic or liquid-slurry systems for waste holding or disposal (Harper et al 2000). A model has been developed to predict pig manure evolution (mass, dry and organic matter, and N contents) and related gaseous emissions nitrous oxide ($N_2O$) from pig excreta up to manure stored before spreading. This model simulates contrasted management systems, including different options for housing (slatted floor or deep litter), outside storage of manure and treatment (anaerobic digestion, biological N removal processes, SLR with straw and solid manure composting (Rigolot et al 2010).

The results of Fournel et al (2012) showed that liquid manure from deep-pit housing systems produces greater emissions of nitrous oxide ($N_2O$) than natural and forced dried manure from belt housing systems. The study of Cabrera et al (1994) on $N_2O$ emissions from poultry litter compared pellets or fine particles. Cumulative emission of $N_2O$ was slightly higher for pelletized (6.8 % of applied N) than for fine-particle litter (5.5 %). Authors indicate that the effect of poultry litter physical characteristics on $N_2O$ emissions can be expected to vary depending on the soil water regime (Cabrera et al 1994).

## Application method

$N_2O$ emissions are strongly dependent on the method and timing of fertilizer application. Manure incorporation

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increased $N_2O$ emissions and yield for the perennial system, but both effects were dependent on the interannual weather variability and crop growth (Webb et al 2014). High temperatures, high wind speed and low rainfall immediately following manure application promote emissions from manures containing a high amount of readily available N. Emissions of $N_2O$ were significantly affected by the timing of manure application, with greatest $N_2O$ emissions measured from manures applied and incorporated into bare soil in warmer and wetter autumn conditions. Mean annual $N_2O$ emissions across all manure treatments were greater from autumn (2 kg $N_2O$–N $ha^{-1}$) than spring (0.35 kg $N_2O$ – N $ha^{-1}$) applications (Bell et al 2016).

The more frequent soil application may increase $N_2O$ emissions, if application occurs during prolonged periods with warm temperature, wet soil and low plant-N uptake. Therefore, a combination of decreased storage time in warm weather and extended winter storage is a viable option in many regions (Hristov et al 2013; Gerber et al 2013). Following field application, infiltration of liquid is influenced by manure organic matter, and retention of ammoniacal N at the soil surface will enhance $NH_3$ volatilization (Petersen and Sommer 2011).

## Final considerations

Farms emit $N_2O$ arising mainly from manure application to soil, faces deposition by grazing animals, or manure storages. The various pathways of $N_2O$ formation described above also apply to the manure environment, but the potential for $N_2O$ emissions will depend on manure management practice. Nitrification and denitrification rates of manure are affected by numerous soil and climatic or seasonal factors.

Emissions of $N_2O$ are significantly affected by the timing of manure application, with greatest $N_2O$ emissions measured from manures applied and incorporated into bare soil in warmer and wetter autumn conditions. Straw cover, floating crust and aeration of slurry showed negative environmental effects. An extended review revealed that more data are needed to better quantify emissions from manure management.

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## Abbreviations

C = carbon
CCH = closed chamber
$CO_{2\,=}$ carbon dioxide
CV = coefficient of variation
d = day
ds = days
DIM = days in milk
DL = deep litter
DM = dry mater
ds = days
FC = flux chamber
FMC = floating measuring chamber
FS = fully slatted
FTIR = Fourier transform infrared spectroscopy
FYM = farmyard manure
GC = gas chromatography
h = hour
LBW = live body weight
LU = live unit (500 kg of LBW)
M = month
MBIGA = mass balance method from 24 h gas sampling
MC = measuring chamber
MY = milk yield
MS = manure system
N = nitrogen
$NH_3$ = ammonium
ODC = open dynamic chamber
RC = respiration chamber
SLR = slurry
TDL = Tuneable Diode Laser absorption spectrometer
TMR = total mixed ration
yr = year
yrs = years
wk = week
wks = weeks

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