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Research Paper

Frequent export of pig slurry for outside storage reduced methane but not ammonia emissions in cold and warm seasons

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ABSTRACT

Manure management is a significant source of methane (CH_4) and ammonia (NH_3), and there is an urgent need for strategies to reduce these emissions. More frequent export of manure for outside storage can lower gaseous emissions from housing facilities, but the longer residence time may then increase emissions during outside storage. This study examined CH_4 and NH_3 emissions from liquid pig manure (pig slurry) removed from the in-house slurry collection pits at three different frequencies, i.e., three times per week ($T_{2.3}$), once per week (T_7), or once after 40 days (T_{40}, reference). The slurry from treatments $T_{2.3}$ and T_7 was transferred for outside storage weekly over four weeks, and slurry from treatment T_{40} once after 40 days, in connection with summer and winter production cycles with growing-finishing pigs. The slurry was stored in pilot-scale storage tanks with solid cover and continuous ventilation. Compared to T_{40}, the treatments $T_{2.3}$ and T_7 increased CH_4 emissions during outside storage, but in-house emissions were reduced even more, and the net effects on total CH_4 emissions from manure management (housing unit and outside storage) were reductions of 18–41% in summer and 53–83% in winter. The frequent slurry export for outside storage led to more NH_3 emissions, except for the treatment $T_{2.3}$, which has slurry funnel inserts beneath the slatted floor. Measurements of *in-vitro* CH_4 production rates suggested that shorter residence time for slurry in pig houses delayed the development of active methanogenic populations, and that this contributed to the reduction of CH_4 emissions.

1. Introduction

Manure management is a significant source of ammonia (NH_3) and greenhouse gas emissions. Ammonia emissions from livestock production constitute 80–90% of agricultural emissions (Webb et al., 2005), and since emissions vary widely depending on animal type, manure management practice and climate (Sommer et al., 2019), there is a need for management-specific data. Livestock production is also responsible for 80% of agricultural methane (CH_4) emissions (Reisinger et al., 2021). The fact that, globally, 90% of this source are associated with enteric emissions, and only 10% with manure management, obscures the fact that for intensive production systems with confined animals the relative importance of CH_4 emissions from manure management can be much higher. Hayek and Miller (2021) reported that CH_4 emissions from intensive livestock production may be 39–90% higher than currently reported in national inventories, and that a part of this gap could be due to an under-estimation of CH_4 emissions from manure management.

There are large regional variations in manure management practices (Gerber et al., 2013), but intensive pig production generally occurs in confined systems with liquid manure management (Varma et al., 2021). This has implications for the greenhouse gas balance of pig production, since the potential for CH_4 emissions is much higher with liquid manure (slurry) than with solid manure management (IPCC, 2019). Gaseous emissions occur from slurry pits in barns as well as outside storage facilities (Gerber et al., 2013). The anaerobic environment of slurry during storage is favorable for fermentation and methanogenic activity, and therefore housing and storage facilities are relevant targets of mitigation measures (Kupper et al., 2020).

Strategies to mitigate unwanted emissions include treatments such as cooling, anaerobic digestion, or slurry acidification (Gerber et al., 2013), or changes in manure management. Slurry cooling in pits can reduce both CH_4 and NH_3 emissions from pig barns, but the carbon footprint of

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cooling depends on the net energy balance of this treatment (Blázquez et al., 2022). Acidification of slurry has a documented potential to reduce both NH_3 and CH_4 emissions (Petersen et al., 2014; Shin et al., 2019; Sokolov et al., 2020), but costs are high. Low-dose acidification in the outside storage tank, however, was recently proposed as a cost-effective alternative for CH_4 mitigation (Ma et al., 2022). Anaerobic digestion can significantly reduce CH_4 emissions from manure during post-digestion storage (Baral et al., 2018), but distance to a centralized biogas plant is often a barrier (Skovsgaard & Jacobsen, 2017). On many farms, therefore, optimization of manure management is the main strategy available to reduce emissions of CH_4 as well as NH_3.

There is a potential for reducing CH_4 emission by increasing the frequency of manure removal from animal houses to outside storage, provided the outside storage temperature is lower compared to the typical climate in animal houses (Philippe & Nicks, 2015). Slurry temperature is an important determinant of methanogenic activity (Elsgaard et al., 2016), and hence frequent export alone may be a CH_4 mitigation strategy in cool or temperate climates. However, the increased residence time of organic matter (volatile solids) in the outside storage could increase CH_4 emissions compared to a reference situation; the trade-off is likely to depend on local climate and season. In Northern Europe the average annual slurry temperature during outdoor storage is around 10 °C, whereas the temperature of pig slurry in housing facilities is closer to 20 °C (Aarnink & Elzing, 1998). However, compared to the slurry temperature in housing systems with climate control there may be significant seasonal variation of slurry temperature during outside storage (Maldaner et al., 2018). This will impact methanogenic activity, which has been found to be 10–100 fold lower during winter compared to summer storage conditions at farm-scale (Husted, 1994) as well as pilot-scale (Petersen et al., 2013). Another unknown factor influencing CH_4 emissions from manure management is the activity and growth of methanogens. More frequent removal of slurry could reduce the extent of adaptation and growth before transfer to an outside storage where a lower storage temperature may delay the development of methanogens. Together this suggests that the effect of frequent export on CH_4 emissions will depend on both site conditions and management. Ammonia emissions will likewise depend on management as well as climate (Sommer et al., 2019), and hence the effects of more frequent export of slurry on NH_3 and CH_4 emissions must be evaluated at different times of the year to determine the overall efficacy of this management strategy.

In this study, two alternative strategies for frequent export of slurry from growing-finishing pigs were investigated with respect to the effect on CH_4 and NH_3 emissions under summer and winter storage conditions. Emissions taking place during the in-house collection period were described in detail by Dalby et al. (2023), and only cumulative emissions and rates from housing units are included in the present study, which reports emissions taking place during outside storage and discusses total emissions with the different export strategies. We hypothesized that CH_4 emissions from outside storage tanks would increase with increasing frequency of export from the pig house during summer, but not winter storage. We further hypothesized that combined CH_4 emissions from pig house and outside storage would be reduced by frequent slurry removal during winter, but not summer storage conditions.

2. Materials and methods

2.1. Slurry management strategies

Slurry was obtained from an experimental pig housing facility at Aarhus University, Viborg Campus, in Western Denmark. Three separate units each had two 11-m^2 pens with 1/3 drained floor and 2/3 slatted floor, and with 15 finishing pigs in each pen. Here, pigs (initially *c.* 30 kg body weight) were fed for 11 weeks during the growing-finishing stage. The units had a negative pressure ventilation system with a diffuse ceiling air inlet and a ceiling-roof top ventilator as principal exhaust unit. The ventilation rates of each room were controlled to maintain an in-house temperature of 21.6 ± 1.7 and 19.5 ± 0.9 °C, and ventilation rates of 2528 ± 943 and 907 ± 344 m^3/h during summer and winter storage experiments, respectively.

Two of the three sections were equipped with one standard shallow slurry collection pit (60 cm depth) per pen, and slurry was either exported for outside storage by day 40 (T_{40}; reference) or at weekly intervals (T_7) starting in week 4 of the growth period. The pits in the third housing unit were equipped with nine funnel-shaped slurry trays (top surface L: 1580 mm and W: 1500 mm) under the floor; here slurry was exported three times per week ($T_{2.3}$). A process flow diagram for the experimental treatments is presented in Figure S1.

2.2. Storage experiments

For the present study, slurry collected during the first 7 weeks of two production cycles starting, respectively, on 28 May and 12 November 2020 were used for pilot-scale storage experiments conducted at the facility described by Petersen et al. (2009). Each storage tank has a volume of 6.5 m^3 and a diameter of 2 m and are partly buried, with 0.7 m above-ground. Each tank is equipped with eight air inlets and a single outlet in the cover connected to a main ventilation duct; the headspace was continuously ventilated, and the ventilation rate logged at 15-min intervals; the average ventilation rate was 94 ± 12 and 110 ± 9.3 m^3/h during summer and winter storage experiments, respectively.

The summer storage experiment took place in the period from 15 June to 6 August 2020, and the winter experiment from 22 November 2020 to 6 January 2021. For the reference treatment, T_{40}, one batch of slurry was transferred to outside storage on day 40 of the production cycle, whereas for treatment T_7 this occurred four times in connection with the weekly export (see transfer dates in Table 1). For treatment $T_{2.3}$

Table 1
Slurry (m^3) exported from pig houses, and in parentheses the total amounts and percentages transferred to each of the storage experiments (split evenly between duplicate reactors)

Season	Transfer date	$T_{2.3}$ [1]	T_7	T_{40}
Summer	2020–06-15	0.32 (0.34; 100%) [2]	1.77 (1.74; 98%)	
	2020–06-18	0.8 + 0.16 (0.94; 98%)	0.88 (0.82; 93%)	
	2020–06-25	0.20 + 0.50 + 0.36 (0.70; 66%)	0.72 (0.60; 83%)	
	2020–07-02	0.13 + 0.35 + 0.32 (0.66; 83%)	0.99 (0.44; 44%)	
	2020–07-07			5.41 (4.48; 83%)
Winter	2020–11-26	0.62 + 0.25 + 0.29 + 0.40 + 0.34 (0.88; 46%)[3]	1.88 (0.90; 48%)	
	2020–12-03	0.34 + 0.51 + 0.35 (0.76; 63%)	0.88 (0.70; 80%)	
	2020–12-10	0.40 + 0.48 + 0.36 (0.88; 71%)	0.88 (0.89; 100%)[2]	
	2020–12-17	0.36 + 0.54 + 0.35 (0.86; 69%)	0.99 (0.90; 91%)	
	2020–12-22			5.63 (4.28; 76%)

[1] Slurry was in most cases removed from the housing unit three times before weekly transfer to the storage tanks.
[2] Volumes of exported slurry were calculated from slurry level changes and dimensions of the slurry collection systems, and the proportions collected for storage were calculated from the amounts in pellet tanks used for transport. Not all exported slurry could be retained for storage.
[3] Slurry for the first batch exported for the storage experiment was collected over 10 days (Nov.16 till Nov. 26, 2020).

with funnel inserts and sub-weekly removal from the pit, the slurry was for logistical reasons collected and kept in one-m^3 HDPE pellet tanks inside the pig housing facility and only transferred for outside storage weekly (Table 1). The HDPE pellet tanks were used for collection and transport to the storage facility, where the slurry from each batch was split between duplicate storage tanks in each of two randomized blocks to have two independent emission measurements.

Slurry samples (500 mL) for analysis were collected from each slurry batch exported from pig houses and stored at −20 °C for later analysis.

2.3. Monitoring of emissions

Concentrations of NH_3, CH_4 and CO_2 in the ventilation air of pig houses were measured in real-time by cavity-ring-down spectroscopy (Picarro G2103/G4301 Analyzer, Picarro Inc., Santa Clara, CA, USA) (Dalby et al., submitted). From the outside storage, emissions of NH_3 and CH_4 from treatments $T_{2.3}$ and T_7 were monitored during eight weeks of outside storage, with fresh addition of pig slurry weekly in each of the first four weeks. Due to the longer in-house retention time, emissions from T_{40} were determined during the last four weeks only following the single transfer. Here, the emissions of NH_3, CH_4, N_2O and CO_2 were quantified as described by Petersen et al. (2009). In short, using a peristaltic pump 15 mL min^{-1} subsamples of the ventilation air from each tank were continuously drawn through a gas washing bottle with 80 mL 20 mM H_3PO_4 for trapping of NH_3. Then the subsamples of ventilation air were transported to a manifold with solenoid valves where gas was collected for 15 s in each 15 min period in alufoil gas sampling bags (SKC Inc., PA, USA).

2.4. Methanogenic activity

Slurry collected from the first batch of slurry transferred in the summer storage experiment (on 15 June 2020 for T_7 and $T_{2.3}$, and on 7 July 2020 for T_{40}) were subsampled for determination of methanogenic activity immediately upon return to the lab following the procedure described by Elsgaard et al. (2016). In short, three-gram portions of sieved (<2 mm) slurry material from each treatment (duplicates) were transferred to each of eight 28 mL test tubes while flushing with N_2 (n = 16). Each test tube was immediately closed (under N_2 headspace) with a butyl rubber stopper and metal crimper, and the tubes were evacuated and refilled with helium three times. To quantify the background of dissolved CH_4, two test tubes per storage tank (four per treatment) were shaken vigorously for 1 min after the addition of 4 mL N_2, and then 3 mL gas was sampled using a 5 mL Hamilton gastight syringe and transferred to 5.9 mL exetainers pre-filled with N_2. The other six test tubes from each slurry sample were incubated at near-ambient temperature (18 °C) in a water-bath. After around 18 h incubation, 3 mL gas samples were taken for determination of CH_4 production rates *c.* 30 min after the addition of 4 mL N_2 to ensure over-pressure; the residual headspace pressure was then measured after gas sampling using a GDH 12AN pressure meter (GHM Messtechnik GmbH, Regenstauf, Germany).

2.5. Analytical methods

Slurry pH and electrical conductivity (EC) were measured by a pH and conductivity meter (Thermo Scientific PC450 meter; Waltham, MA, USA). Slurry dry matter (DM) was determined after drying at 105 °C for 24 h, and volatile solids (VS) after an additional three hours at 550 °C. Total N (TN) and ammoniacal N (TAN) were determined by Kjeldahl digestion (Kjeltec; Foss, Hillerød, Denmark). Acetate and total VFA were determined as described in Feng et al. (2022).

Concentrations of CH_4, N_2O and CO_2 were determined by gas chromatography on an Agilent 7890 GC system interfaced with a CTC CombiPal autosampler (Agilent, Nærum, Denmark). The instrument was equipped with two separate channels. The first channel had a back-flushed pre-column (Hayesep P) and main column (Porapak Q) connected to a valve directing the carrier gas (N_2 at a rate of 45 mL min^{-1}) to either a flame ionization detector (FID) for CH_4 analysis or an electron capture detector (ECD) for N_2O analysis. Ar-CH_4 (95 %/5 %) at 40 mL min^{-1} was the make-up gas for the ECD, while the FID received 45 mL min^{-1} H_2, 450 mL min^{-1} air and 20 mL min^{-1} N_2. The second channel (Porapak Q) used He at 42 mL min^{-1} as carrier and was connected to a thermocouple detector (TCD) for CO_2 analysis, and with He at 7 mL min^{-1} as the make-up gas. Temperatures of inlet and columns were the same for all gases at 80 °C, while the temperatures of FID, ECD and TCD were 200, 325 and 250 °C, respectively (Petersen et al., 2012). Colorimetric analysis was used to measure the ammonia trapped in 20 mM H_3PO_4 (Keeney & Nelson, 1982).

2.6. Data analyses

For outside storage experiments, the time-averaged concentrations of CH_4, CO_2 and NH_3, together with logged ventilation rates, were used to calculate weekly average emission rates, and cumulative emissions during the entire monitoring period. Weekly average emissions were scaled to the total cumulative VS exported to align with emissions from housing units.

Total in-house CH_4 and NH_3 emissions were also calculated as the product of ventilation rates and gas concentrations. For all treatments, the in-house slurry CH_4 emission was calculated as total emission during 0–40 days corrected for enteric emissions, which were calculated by assuming that 0.2 % of gross energy intake was converted to CH_4 (Jørgensen, 2011).

All statistical tests were performed using R version 3.6.3. Differences in slurry characteristics between treatments and seasons were tested with linear models using the *lm* function, where treatment and season were fixed effects. The model structure was: log(slurry characteristic) ~ treatment + season + treatment × season. Analysis of similarities (ANOSIM) was used to evaluate the significant differences of slurry between treatments, using the vegan package in R; the measured slurry characteristics were scaled before testing for similarities. Differences in CH_4 production rates in lab incubations were evaluated with the Kruskal-Wallis test (Kruskal & Wallis, 1952). Differences in gas emission rates during outside storage were tested by mixed effect models using the lme4 package, where treatment, season and week were fitted as fixed effects and storage tank ID was a random effect. The model structure was: log(CH_4 or NH_4 emission rates) ~ treatment + season + treatment × season + week + (1|tank ID). For testing difference in gas emission rates in pig houses, we used linear models with season, treatment and date as fixed factors. The model structure was: log(CH_4 or NH_4 emission rates) ~ treatment + season + treatment × season + date. Pairwise comparisons with Tukey's adjusted p-values were then performed using the emmeans package within each model.

3. Results

3.1. Environmental conditions during summer and winter storage

The average daily air temperature during outside summer and winter storage experiments were 15.4 ± 3.7 and 3.4 ± 2.6 °C, respectively (Fig. 1). The highest air temperatures were observed within the first two weeks of the summer storage experiment. In the winter storage experiment, the air temperature decreased from the 5th week of the storage period to below 0 °C for several days. Precipitation during summer and winter storage periods was 114 and 56 mm, respectively, but since the storage tanks were covered, but actively ventilated to simulate open storage, this did not affect emissions.

3.2. Slurry characteristics

The VS content of fresh slurry constituted 72–81% of total solids (TS), with slightly lower proportions in summer compared to winter

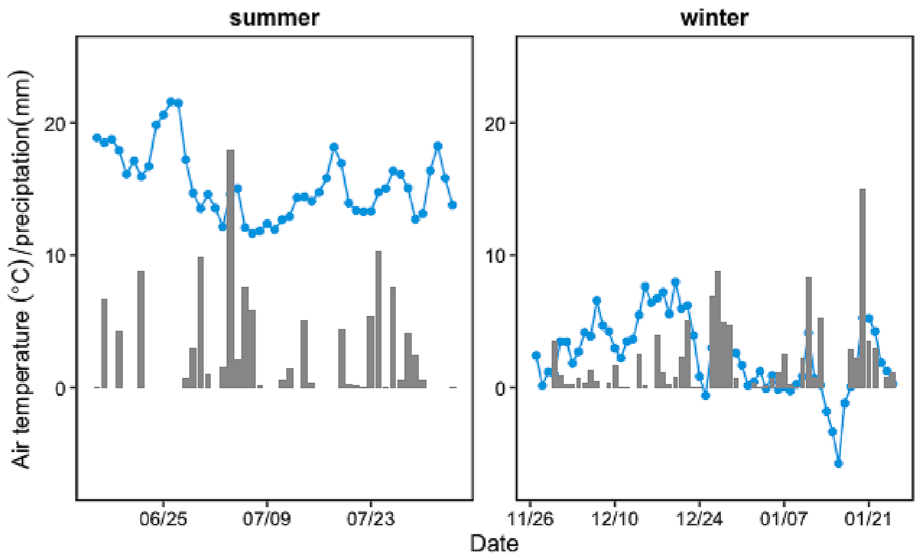

Fig. 1. Daily average outside air temperature (blue points) and precipitation (gray bars) during summer and winter storage experiments.

Table 2
Characteristics of fresh slurry added to storage tanks.

	T_{40} (reference)		T_7		$T_{2.3}$	
	summer	winter	summer	winter	summer	winter
TS, %	4.3 ± 0.6^{ab}	6.8 ± 1.0^{ab}	8.5 ± 2.2^{a}	7.9 ± 0.8^{ab}	8.2 ± 0.8^{b}	8.8 ± 1.1^{ab}
VS, %	3.1 ± 0.4^{a}	5.2 ± 0.9^{ab}	6.7 ± 1.9^{b}	6.4 ± 0.7^{b}	6.4 ± 0.7^{b}	7.1 ± 0.9^{b}
VS/TS, %	72 ± 1.0^{a}	77 ± 1.4^{b}	79 ± 3.0^{bc}	80 ± 0.8^{bc}	78 ± 1.9^{bc}	81 ± 1.2^{c}
pH	7.0 ± 0.3^{a}	6.8 ± 0.1^{a}	6.6 ± 0.2^{a}	6.8 ± 0.1^{a}	6.6 ± 0.1^{a}	6.5 ± 0.4^{a}
TAN, g N kg^{-1}	2.8 ± 0.6^{ab}	3.0 ± 0.2^{ab}	2.6 ± 0.6^{a}	2.2 ± 0.2^{ab}	2.7 ± 0.6^{b}	2.3 ± 0.3^{ab}
TN, g N kg^{-1}	3.7 ± 1.0^{ab}	4.4 ± 0.2^{ab}	4.8 ± 1.1^{a}	4.3 ± 0.4^{ab}	4.6 ± 0.9^{b}	4.5 ± 0.2^{ab}
Acetate, g kg^{-1}	6.7 ± 0.2^{bc}	6.4 ± 0.3^{bc}	7.3 ± 1.4^{c}	4.7 ± 0.5^{a}	7.1 ± 1.6^{c}	5.4 ± 0.1^{ab}
Total VFA, g kg^{-1}	12.9 ± 0.5^{b}	13.4 ± 0.7^{b}	14.1 ± 3.0^{b}	9.4 ± 1.0^{a}	13.8 ± 3.4^{b}	11.9 ± 1.0^{b}

Data shown as mean ± standard deviation ($n \geq 4$); The letters are from post-hoc Tukey honest significant difference tests run on linear models; letters indicate significant statistical difference between treatments and seasons ($p < 0.05$).

storage. The content of slurry VS was lower in T_{40} than in the other two treatments, although the difference was not statistically significant in the winter storage experiment. Slurry pH values were comparable between 6.5 and 7.0 (Table 2). There was little difference between treatments in TAN and TN concentrations which were 2.2–3.0 and 3.7–4.8 g N kg^{-1}, respectively. Slurry acetate concentrations were higher in summer than in winter, but the total VFA were similar, except for T_7 which was lower in the winter experiment. An ANOSIM analysis showed that there were no significant differences in slurry characteristics between treatments ($R = -0.007$, $p = 0.56$).

By the end of the winter storage experiment, a thin surface crust had developed in all storage tanks, whereas no crusting was observed during summer storage.

3.3. Ammonia emissions

Measurements of NH_3 emissions during outside storage included only $T_{2.3}$ and T_7 during the first four weeks. In both summer and winter storage periods, these treatments were characterised by high emissions during the first week which were followed by a sharp decline (Fig. 2). Ammonia emissions from the reference treatment (T_{40}) during the last four weeks of the storage experiment were similar to, or lower, than those of the other two treatments. In the summer storage period, the NH_3 emission rates increased slightly in all treatments during the last four weeks, while in the winter experiment, the emission rates remained low. Nitrous oxide emissions could not be detected, and the concentration of N_2O in ventilation air was always close to that of ambient air (0.330 ppm).

Cumulative NH_3 emissions during housing (day 0–40) were in the range of 37–127 g N pig^{-1} (Table 3). Treatment $T_{2.3}$ showed significantly lower in-house NH_3 emissions at rates of 1.5 ± 0.9 and 0.9 ± 0.3 g N pig^{-1} day^{-1} during summer and winter experiments, respectively. The highest in-house emission rates were observed for T_7, followed by T_{40}, in both seasons; they were 2- to 3.3- fold higher than in treatment $T_{2.3}$. In contrast, $T_{2.3}$ showed the highest emission during the outside storage in the summer at 1.6 ± 0.7 g N pig^{-1} day^{-1}. In the winter storage experiment, NH_3 emissions were low in all treatments at 0.18–3.2 g N pig^{-1} day^{-1}, where slightly higher emissions were determined in T_7.

The overall NH_3 emissions from treatment T_7, including emissions during in-house collection and outside storage, were higher than from the reference treatment, T_{40}, i.e., 26% higher during the summer and 55% higher during the winter storage experiment. In contrast, overall NH_3 emissions from $T_{2.3}$ were reduced by 44% in winter and comparable to T_{40} in summer (Table 3). In T_7 and T_{40}, most of the NH_3 emission occurred from housing units and accounted for 78% or more of total NH_3 emissions during the measurement periods. In contrast, treatment $T_{2.3}$ with funnel inserts significantly reduced in-house NH_3 emissions, but this was accompanied by an increase in the emissions from outside storage.

3.4. Methane emissions

Methane emissions during outside storage, expressed as average daily rates during the 7-day sampling periods, were significantly higher

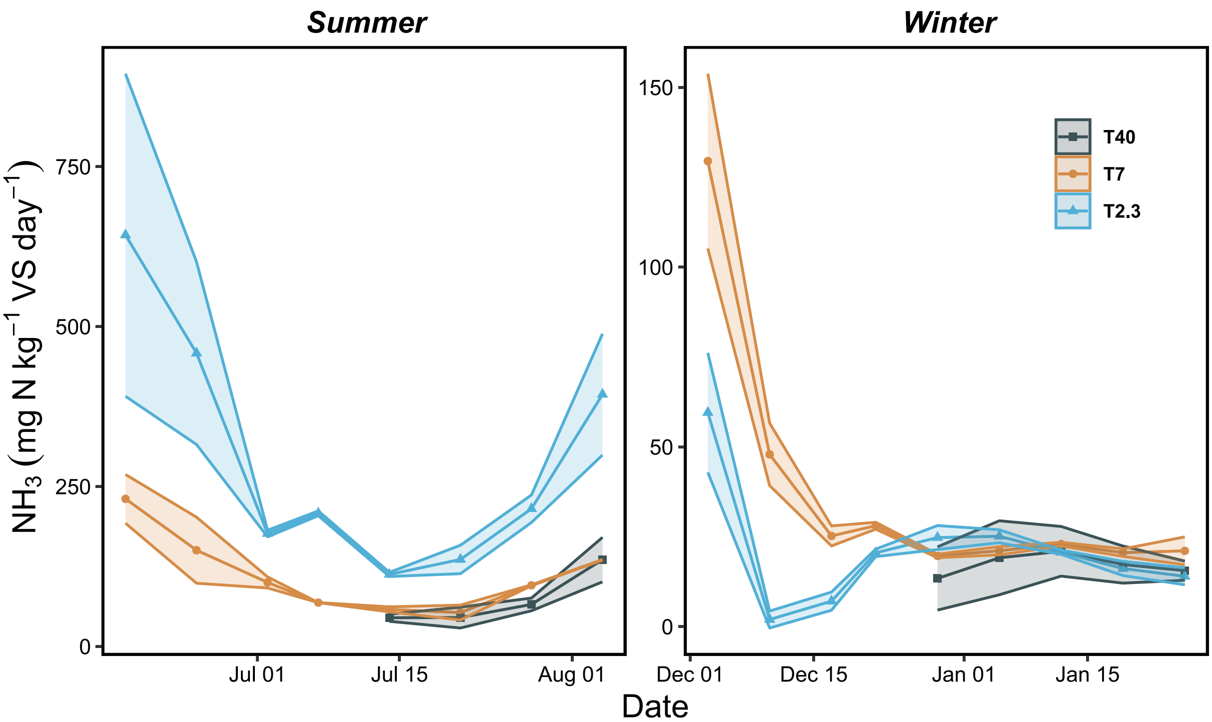

Fig. 2. NH_3 emission during outside storage of pig slurry exported at different frequencies, i.e., three times per week ($T_{2.3}$), once per week (T_7) or after a collection period of 40 d (T_{40}). The lines connect the weekly mean NH_3 emission rates, and shaded areas show the range of emission rates ($n = 2$).

Table 3
Summary of NH_3 emissions from pig housing units and outside storage tanks. Efficiency represents the change in emissions with shorter retention time, negative values representing a reduction.

Season	Treatment	In-house emission[1]		Outside storage emission		Total emission	Efficiency
		Daily rate ($g N pig^{-1} day^{-1}$)	Cumulative ($g N pig^{-1}$)	Daily rate ($g N pig^{-1} day^{-1}$)	Cumulative ($g N pig^{-1}$)	($g N pig^{-1}$)	(%)
Summer	T_{40}	3.0 ± 1.2	116	0.45 ± 0.26	12.6	129	
	T_7	3.3 ± 1.7	127	0.70 ± 0.22	35.2	162	26.1
	$T_{2.3}$	1.5 ± 0.9	58.4	1.6 ± 0.7	78.6	137	6.5
Winter	T_{40}	2.1 ± 0.5	85.7	0.18 ± 0.03	6.2	91.9	
	T_7	3.0 ± 0.8	122	0.32 ± 0.18	20.0	142	54.5
	$T_{2.3}$	0.9 ± 0.3	37.1	0.21 ± 0.11	14.6	51.7	−43.7

Data are shown as mean ± sd.
[1]In-house emissions only include the emissions from the first 40 days in the pig house.
[2]Outside emissions include the whole storage periods, 50 days for summer and 61 days for winter.

during summer compared to winter storage ($p < 0.05$, Fig. 3). Significant differences were also observed between treatments $T_{2.3}$ and T_{40}, as well as between $T_{2.3}$ and T_7 (both $p < 0.05$).

The highest CH_4 emission rate observed during outside storage was in treatment $T_{2.3}$ during the first week of summer storage, and this was followed by a steep decline, from 0.27 to 0.17 g C kg^{-1} VS day^{-1}. Except for the first week of storage, the CH_4 emissions from $T_{2.3}$ and T_7 followed the same trend in both summer and winter experiments, but with consistently lower rates from $T_{2.3}$ compared to T_7. For the reference treatment (T_{40}) with longer in-house retention time, the export occurred halfway through the pig-fattening period. Here, the CH_4 emission rate was highest among treatments during the first week under both summer and winter storage conditions but subsequently, with no further input of exported slurry, the emissions of CH_4 in all treatments were comparable at < 0.1 and < 0.01 g C kg^{-1} VS day^{-1} during summer and winter storage, respectively.

Total CH_4 emissions during housing (day 0–40) were in the range 1.2–4.5 g C pig^{-1} day^{-1}, which included enteric and manure emissions (Table 4). Daily enteric emissions, as calculated from feed intake, were comparable between treatments at 0.81–0.96 g C pig^{-1} day^{-1}, with slightly higher emissions in the winter experiment. Treatment T_{40} showed the highest cumulative in-house CH_4 emissions from manure at rates of 85 and 140 g C pig^{-1} in summer and winter, respectively. This was around two times greater than emissions from T_7, and three or 12 times higher than $T_{2.3}$ in summer and winter experiments. In contrast, daily rates during outside storage were not different between treatments ($p > 0.05$), except that it tended to be higher from T_7 during summer storage. Also, CH_4 emission rates were higher during summer compared to winter storage. Due to the longer outside storage times, the cumulative CH_4 emissions from treatments T_7 (43.5 g C pig^{-1}) and $T_{2.3}$ (29.6 g C pig^{-1}) compared to T_{40} during outside storage were 3- and 2-fold higher during summer storage, and also tended to be higher during winter storage where the range observed was 12.6–18.4 g C pig^{-1} (Table 4).

Taken together, the total CH_4 emissions during in-house and outside storage were reduced by 18–53% when increasing the slurry export frequency from 40 d (T_{40}) to weekly (T_7), and by 41–83% with export three times per week ($T_{2.3}$). The total emissions, and reductions with frequent removal and export for outside storage, were higher in the winter experiment compared to the summer experiment, although this was in part because of higher in-house emissions (Table 4).

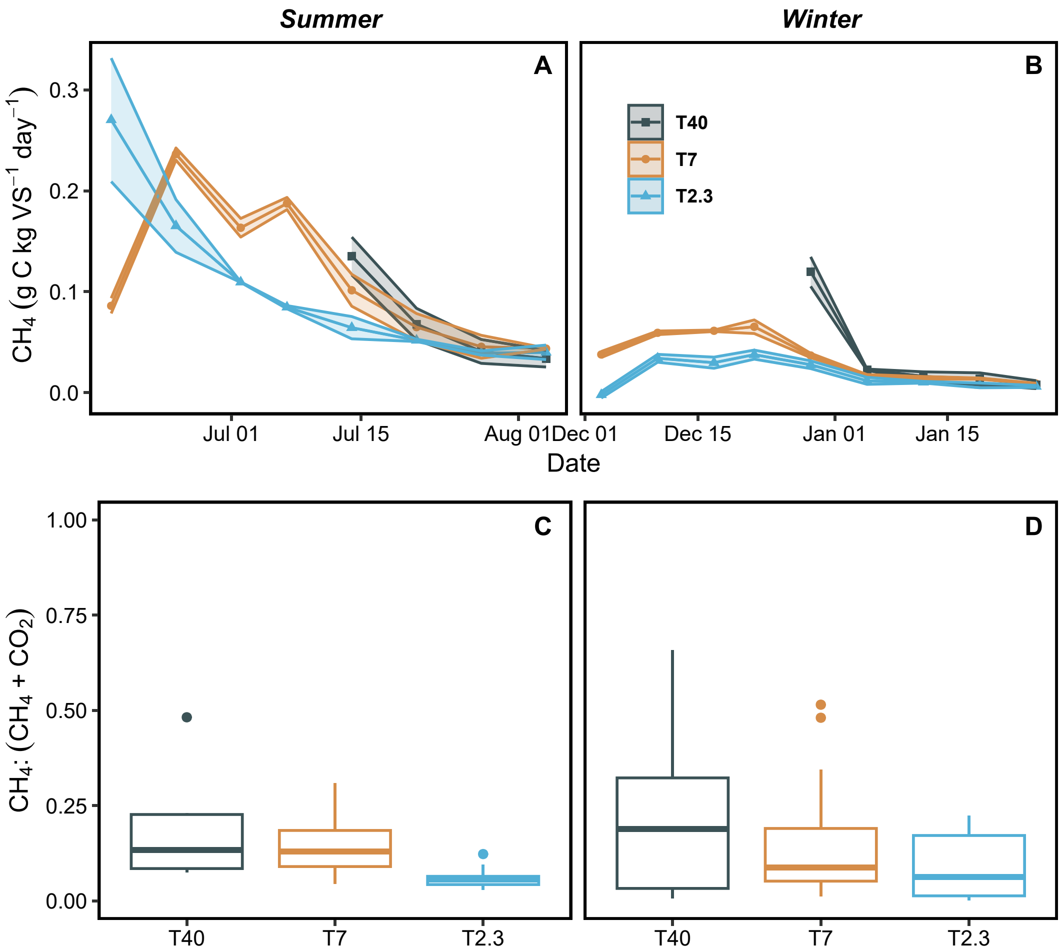

Fig. 3. The upper panel shows CH_4 emissions during outside storage of pig slurry exported at different frequencies, i.e., three times per week ($T_{2.3}$), once per week (T_7) or after a collection period of 40 d (T_{40}) during summer (A) and winter (B) storage experiments. The lines connect the weekly means and shaded areas show the range of emission rates ($n = 2$). The lower panel shows the ratios between CH_4 and ($CH_4 + CO_2$) in the different treatments during summer (C) and winter (D) storage experiments.

Table 4
Summary of CH_4 emissions from pig housing units and outside storage tanks. Efficiency represents the change in emissions with shorter retention time, negative values representing a reduction.

Season	Treatment	In-house emission			Outside storage emission		Total emission	Efficiency[1]
		Total (g C pig^{-1} day^{-1})	Enteric (g C pig^{-1} day^{-1})	Slurry (g C pig^{-1})	Slurry (g C pig^{-1} day^{-1})	Slurry (g C pig^{-1})	Slurry (g C pig^{-1})	(%)
Summer	T_{40}	3.2 ± 1.9	0.87 ± 0.23	85	0.56 ± 0.22	15.7	101	
	T_7	2.0 ± 0.95	0.85 ± 0.23	39.6	0.85 ± 0.44	43.5	83.1	−17.7
	$T_{2.3}$	1.7 ± 0.9	0.81 ± 0.23	30.2	0.60 ± 0.19	29.6	59.8	−40.8
Winter	T_{40}	4.5 ± 2.0	0.96 ± 0.24	140	0.36 ± 0.46	12.6	153	
	T_7	2.4 ± 0.7	0.95 ± 0.24	54.3	0.31 ± 0.21	18.4	72.7	−52.7
	$T_{2.3}$	1.2 ± 0.59	0.92 ± 0.22	11.4	0.24 ± 0.16	14	25.4	−83.4

Data are shown as mean ± sd.
[1] Efficiency calculations only refer to in-house slurry CH_4 emissions (total minus enteric emissions) and CH_4 emissions during outside storage.

3.5. *Methanogenic activity*

The proportions of carbon emitted as CH_4 were calculated from emissions of CH_4 and CO_2 (Fig. 3). Treatment $T_{2.3}$ was characterized by a significantly lower CH_4: ($CH_4 + CO_2$) ratio than the other two treatments in both seasons ($p < 0.05$).

Methanogenic activity was evaluated in the summer experiment by *in-vitro* measurements of CH_4 production rates in slurry sampled on the first day of outside storage (15 June 2020 for T_7 and $T_{2.3}$, and 7 July 2020 for T_{40}). Although slurry characteristics in the three treatments were similar (Table 2), there were thus substantial differences with respect to methanogenic activity (Fig. 4). The treatment T_{40} produced CH_4 at a rate of 0.12 g C kg^{-1} VS day^{-1}, which was 1.5 and 2.3 times greater than the rates of T_7 and $T_{2.3}$, respectively (Fig. 4).

4. Discussion

4.1. *Ammonia emissions*

Overall NH_3 emissions were dominated by the contribution from

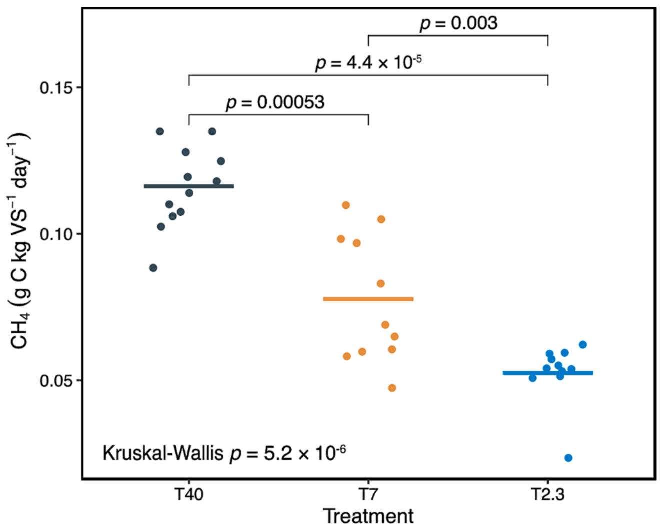

Fig. 4. Methane production rates of slurry sampled at the time of export from three different export frequencies, i.e., three times per week ($T_{2.3}$), once per week (T_7) or after a collection period of 40 d (T_{40}), in the summer storage experiment. Sampling took place June 15, 2020 in treatments T_7 and $T_{2.3}$, and July 7, 2020 for T_{40}. The individual data points represent 12 individual rate measurements per treatment, and horizontal lines show the mean values. All slurry samples were incubated at 18 °C.

housing units with traditional pits except in treatment $T_{2.3}$, where funnel inserts in the pits successfully lowered in-house NH_3 volatilisation by reducing the liquid surface exposed to ventilation air (Ye et al., 2008). Ammonia emissions were significantly higher in the summer experiment, which was in accordance with the higher in-house temperature and ventilation rates. Ammonia emissions from floors have been estimated at 30–50% of total emissions from pig houses (Aarnink & Elzing, 1998; Kai et al., 2006), and NH_3 emissions from both pits and floor surfaces are affected by ventilation rate as well as temperature (Petersen et al., 2016).

Frequent export of pig slurry resulted in higher NH_3 emissions during subsequent outside storage, and higher overall emissions except for $T_{2.3}$ in winter, possibly because of some crust formation. Ammonia emissions during outside storage varied from 0.003 to 0.17 g $m^{-2}h^{-1}$, which was at the low end of the range 0.01 to 0.92 g $m^{-2}h^{-1}$ reported for pilot-scale experiments in a recent review(Kupper et al., 2020), possibly because the slurry pH was at or below 7 in the present study. The lower emissions compared to housing units could be explained by the much lower ventilation rate used to simulate open storage conditions (Saha et al., 2010).

The seasonal pattern was expected (Grant & Boehm, 2020) and confirms the importance of covering storages with livestock slurry to lower slurry temperature in warm climates (Huang and Shang, 2006). Frequent slurry export increased cumulative NH_3 emissions from treatments $T_{2.3}$ and T_7 during outside storage in part because of the longer outside storage period, but it is also possible that mixing after each weekly addition of fresh slurry enhanced NH_3 release from these treatments (Sommer et al., 1993; Van der Stelt et al., 2007).

4.2. Methane emissions

The levels of CH_4 emissions in this study were relatively low at around 0.1–0.2 g C kg^{-1} VS day^{-1} most of the time during summer storage, and 0.02–0.04 g C kg^{-1} VS day^{-1} during winter storage (Fig. 3). For comparison, Massé et al. (2003) reported emissions corresponding to *c.* 0.07 and 0.4 g C kg^{-1} VS day^{-1} for storage of a comparable pig slurry (4.9% DM) at 10 and 15 °C, respectively, and similar rates were reported for winter and summer storage of pig slurry by Petersen et al. (2013). The summer experiment was the first of four production cycles and was initiated after a period of several months without animals in the housing facility. Lower in-house CH_4 emissions from pig slurry in the summer compared to the winter experiment (Table 4) indicate that the batch of older slurry material, left in the pit to serve as a methanogenic inoculum (Habtewold et al., 2018; Haeussermann et al., 2006; Le Riche et al., 2020), was less active than expected, and a reduced ability of methanogens to inoculate the fresh material could thus have influenced the level of subsequent outside CH_4 emissions.

The overall CH_4 emissions from pig slurry were reduced by more frequent export, with the greatest reduction of 83 % for treatment $T_{2.3}$ in the winter storage experiment. The outside air temperature was at or below 5°C during most of the winter storage period and resulted in low CH_4 emissions independent of treatments. This effect of temperature was in agreement with a study of dairy slurry storage (Cardenas et al., 2021), and with a study reporting that lowering the temperature of pig slurry from 35 to 20 °C during storage reduced CH_4 emission by 90% (Im et al., 2022). Also, Safley and Westerman (1994) reported a linear decrease of CH_4 production rates in pig and cattle slurry with temperature declining from 25 to 10 ℃. Dalby et al. (2021) discussed mechanisms that may be involved in the regulation of CH_4 emissions and argued that methanogens are adapted to specific temperature ranges, and that, in addition to the direct effect of temperature on organic matter decomposition, there will be a need for successional changes in the methanogenic community of the slurry in a colder outside storage delaying emissions.

In the summer storage experiment, the longer residence time of treatments $T_{2.3}$ and T_7 in the outside storage tanks was accompanied by higher CH_4 emissions, as hypothesized. However, there was still an overall reduction of total CH_4 emissions from housing and storage, in opposition to our second hypothesis which assumed that reduced in-house emissions would be replaced by higher emissions from outside storage if temperatures were similar. The length of storage was shorter than under practical storage conditions, and thus in theory the balance between treatments could change during prolonged storage. However, the emission of CH_4 always declined after the last export from housing units, with reductions ranging from 50 to 90%, presumably because labile organic matter was depleted. If each transfer of slurry from pig houses to the outside storage tank can be considered as an independent batch with emissions that are defined by slurry composition and methanogenic activity, as modified by storage temperature, then the qualitative effects observed in these storage periods should be representative.

The *in-vitro* measurements of CH_4 production rates indicated there was less methanogenic activity in slurry from treatments $T_{2.3}$ and T_7 entering the outside storage compared to treatment T_{40} (Fig. 4), and CH_4: (CH_4 + CO_2) ratios also indicated that a higher proportion of the degraded VS was metabolised via methanogenesis in the reference treatment compared to frequent removal strategies (Fig. 3). Further, Feng et al. (2022), in a companion study, found that specific methane production activity in slurry samples from treatment $T_{2.3}$ amended with acetate did not respond to an increase in the incubation temperature from < 20 to > 25 °C, while this was the case for treatments T_7 and T_{40}. A lower potential for CH_4 production in pig slurry from frequent export strategies at the time of export may partly explain why in-house emissions were not fully replaced by emissions from outside storage.

Across both seasons a significant reduction of total CH_4 emissions may thus be achievable by more frequent export. In a study with a different pig housing design, Amon et al. (2007) reported a 55–60% reduction of total CH_4 emissions from pig slurry during storage with daily removal compared to a reference without daily removal. A similar average effect across summer and winter experiments was seen with treatment $T_{2.3}$, whereas the effect was somewhat less with treatment T_7 (Table 4).

The in-house emission of CH_4 from slurry was calculated by subtracting enteric emissions assuming that 0.2% of gross energy intake (Y_m) was emitted as CH_4 (Jørgensen, 2011). Different studies have reported Y_m values ranging from 0.2 to 0.6 % (Dämmgen et al., 2012; Jørgensen, 2011; Jørgensen et al., 2011), and hence the lower value of Y_m used here could have over-estimated the contribution of in-house CH_4 emissions from slurry. On the other hand, with a higher Y_m the relative effects of frequent removal on total CH_4 emissions from slurry would be even greater.

In conclusion, the treatment effects on overall CH_4 emissions from pig slurry were consistent with the seasonal difference in average outside storage temperature, but there was also evidence that a delay in the development of a methanogenic potential contributed to reduce emissions. The results confirmed that frequent export can be a CH_4 mitigation strategy in temperate climates. Frequent export was not in itself a mitigation strategy for NH_3 emissions; while funnel inserts significantly reduced emissions from housing units as well as outside storage during winter, there was a higher potential for NH_3 emissions during the extended outside summer storage that will require other measures, such as acidification, a surface crust, or a solid cover. Frequent export has no additional cost, apart from the labour involved, and can be integrated into existing manure management practices. Since 2023, weekly export is mandatory on farms with finishing pigs in Denmark. The adoption of funnel inserts is most likely to occur in new pig houses, where potentially the value of reduced NH_3 and CH_4 emissions could help reduce investment costs.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2023.07.014.

References

Aarnink, A.J.A., Elzing, A., 1998. Dynamic model for ammonia volatilization in housing with partially slatted floors, for fattening pigs. Livestock Prod. Sci., 53, 2, 153–169. https://doi.org/10.1016/S0301-6226(97)00153-X.

Amon, B., Kryvoruchko, V., Frohlich, M., Amon, T., Pollinger, A., Mosenbacher, I., Hausleitner, A., 2007. Ammonia and greenhouse gas emissions from a straw flow system for fattening pigs: Housing and manure storage. Livest. Sci. 112 (3), 199–207. https://doi.org/10.1016/j.livsci.2007.09.003.

Baral, K.R., Jego, G., Amon, B., Bol, R., Chantigny, M.H., Olesen, J.E., Petersen, S.O., 2018. Greenhouse gas emissions during storage of manure and digestates: Key role of methane for prediction and mitigation. Agr. Syst. 166, 26–35. https://doi.org/10.1016/j.agsy.2018.07.009.

Blázquez, C.S., Borge-Diez, D., Nieto, I.M., Mate-Gonzalez, M.A., Martin, A.F., Gonzalez-Aguilera, D., 2022. Geothermal Heat Pumps for Slurry Cooling and Farm Heating: Impact and Carbon Footprint Reduction in Pig Farms. Sustainability 14 (10). 10.3390/su14105792.

Cardenas, A., Ammon, C., Schumacher, B., Stinner, W., Herrmann, C., Schneider, M., Weinrich, S., Fischer, P., Amon, T., Amon, B., 2021. Methane emissions from the storage of liquid dairy manure: Influences of season, temperature and storage duration. Waste Manag. 121, 393–402. https://doi.org/10.1016/j.wasman.2020.12.026.

Dalby, F.R., Hafner, S.D., Petersen, S.O., VanderZaag, A.C., Habtewold, J., Dunfield, K., Chantigny, M.H., Sommer, S.G., 2021. Understanding methane emission from stored animal manure: A review to guide model development. J. Environ. Qual. 50 (4), 817–835. https://doi.org/10.1002/jeq2.20252.

Dalby, F.R., Hansen, M.J., Guldberg, L.B., Hafner, S.D., Feilberg, A., 2023. Simple Management Changes Drastically Reduce Pig House Methane Emission in Combined Experimental and Modeling Study. Environ. Sci. Tech. 57 (9), 3990–4002. https://doi.org/10.1021/acs.est.2c08891.

Dämmgen, U., Schulz, J., Klausing, H.K., Hutchings, N.J., Haenel, H.D., Rosemann, C., 2012. Enteric methane emissions from German pigs. Landbauforschung 62 (3), 83–96.

Elsgaard, L., Olsen, A.B., Petersen, S.O., 2016. Temperature response of methane production in liquid manures and co-digestates. Sci. Total Environ. 539, 78–84. https://doi.org/10.1016/j.scitotenv.2015.07.145.

Feng, L., Guldberg, L.B., Hansen, M.J., Ma, C., Ohrt, R.V., 2022. Impact of slurry removal frequency on CH4 emission and subsequent biogas production; a one-year case study. Waste Manag. 149, 199–206. https://doi.org/10.1016/j.wasman.2022.06.024.

Gerber, P.J., Hristov, A.N., Henderson, B., Makkar, H., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J., Rotz, A., Dell, C., Adesogan, A.T., Yang, W.Z., Tricarico, J.M., Kebreab, E., Waghorn, G., Dijkstra, J., Oosting, S., 2013. Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: a review. Animal 7 (Suppl 2), 220–234. https://doi.org/10.1017/S1751731113000876.

Grant, R.H., Boehm, M.T., 2020. Ammonia Emissions from Differing Manure Storage Facilities at Two Midwestern Free-Stall Dairies. Atmos. 11 (10), 1108. https://doi.org/10.3390/atmos11101108.

Habtewold, J., Gordon, R., Sokolov, V., VanderZaag, A., Wagner-Riddle, C., Dunfield, K., 2018. Targeting Bacteria and Methanogens To Understand the Role of Residual Slurry as an Inoculant in Stored Liquid Dairy Manure. Appl. Environ. Microbiol. 84 (7). 10.1128/AEM.02830-17.

Haeussermann, A., Hartung, E., Gallmann, E., Jungbluth, T., 2006. Influence of season, ventilation strategy, and slurry removal on methane emissions from pig houses. Agr. Ecosyst. Environ. 112 (2–3), 115–121. https://doi.org/10.1016/j.agee.2005.08.011.

Hayek, M.N., Miller, S.M., 2021. Underestimates of methane from intensively raised animals could undermine goals of sustainable development. Environ. Res. Lett. 16 (6), 063006 https://doi.org/10.1088/1748-9326/ac02ef.

Husted, S., 1994. Seasonal variation in methane emission from stored slurry and solid manures (0047-2425). https://doi.org/10.2134/jeq1994.00472425002300030026x.

Huang, J.-C., Shang, C., 2006. Advanced Physicochemical Treatment Processes. In: Wang, L.K., Hung, Y.T., Shammas, N.K. (Eds.), Handbook of Environmental Engineering, 4. Humana Press, pp. 47–79. https://doi.org/10.1007/978-1-59745-029-4_2.

Im, S., Mostafa, A., Lim, K.H., Kim, I., Kim, D.H., 2022. Automatic temperature rise in the manure storage tank increases methane emissions: Worth to cool down! Sci. Total Environ. 823, 153533 https://doi.org/10.1016/j.scitotenv.2022.153533.

IPCC. (2019). 2019 Refinement to the 2006 IPCC guidelines for national greenhouse gas inventories. In: Institute for Global Environmental Strategies Hayama.

Jørgensen, H., 2011. Methane emission from pigs. *Report.* Aarhus University.

Jørgensen, H., Theil, P., K. , & Knudsen, K.E.B., 2011. Enteric Methane Emission from Pigs. In G.C. Elias (Ed.), Planet Earth 2011 (pp. Ch. 27). IntechOpen. https://doi.org/10.5772/24377.

Kai, P., Kaspers, B., van Kempen, T., 2006. Modeling sources of gaseous emissions in a pig house with recharge pit. Transactions of the Asabe 49 (5), 1479–1485. https://doi.org/10.13031/2013.22040.

Keeney, D., Nelson, D., 1982. Nitrogen inorganic forms. In: Page, A.L. (Ed.), Methods of soil analysis part II, Vol. 643. American Society of Agronomy.

Kruskal, W.H., Wallis, W.A., 1952. Use of ranks in one-criterion variance analysis. J. Am. Stat. Assoc. 47 (260), 583–621.

Kupper, T., Hani, C., Neftel, A., Kincaid, C., Buhler, M., Amon, B., VanderZaag, A., 2020. Ammonia and greenhouse gas emissions from slurry storage - A review. Agr. Ecosyst. Environ. 300 https://doi.org/10.1016/j.agee.2020.106963.

Le Riche, E.L., VanderZaag, A.C., Wood, J.D., Wagner-Riddle, C., Dunfield, K., McCabe, J., Gordon, R., 2020. Does overwintering change the inoculum effect on methane emissions from stored liquid manure? J. Environ. Qual. 49 (2), 247–255. https://doi.org/10.1002/jeq2.20003.

Ma, C., Dalby, F.R., Feilberg, A., Jacobsen, B.H., Petersen, S.O., 2022. Low-Dose Acidification as a Methane Mitigation Strategy for Manure Management. ACS Agric. Sci. Technol. 2 (3), 437–442. https://doi.org/10.1021/acsagscitech.2c00034.

Maldaner, L., Wagner-Riddle, C., VanderZaag, A.C., Gordon, R., Duke, C., 2018. Methane emissions from storage of digestate at a dairy manure biogas facility. Agric. For. Meteorol. 258, 96–107. 10.1016/j.agrformet.2017.12.184.

Massé, D.I., Croteau, F., Patni, N., Masse, L., 2003. Methane emission from dairy cow and swine manure slurries stored at 10 °C AND 15 °C. Can. Biosyst. Eng. 45, 6.1–6.6.

Petersen, S.O., Skov, M., Droscher, P., Adamsen, A.P., 2009. Pilot scale facility to determine gaseous emissions from livestock slurry during storage. J. Environ. Qual. 38 (4), 1560–1568. https://doi.org/10.2134/jeq2008.0376.

Petersen, S.O., Hoffmann, C.C., Schafer, C.M., Blicher-Mathiesen, G., Elsgaard, L., Kristensen, K., Larsen, S.E., Torp, S.B., Greve, M.H., 2012. Annual emissions of CH4 and N2O, and ecosystem respiration, from eight organic soils in Western Denmark managed by agriculture. Biogeosciences 9 (1), 403–422. https://doi.org/10.5194/bg-9-403-2012.

Petersen, S.O., Dorno, N., Lindholst, S., Feilberg, A., Eriksen, J., 2013. Emissions of CH4, N2O, NH3 and odorants from pig slurry during winter and summer storage. Nutr. Cycl. Agroecosyst. 95 (1), 103–113. https://doi.org/10.1007/s10705-013-9551-3.

Petersen, S.O., Hojberg, O., Poulsen, M., Schwab, C., Eriksen, J., 2014. Methanogenic community changes, and emissions of methane and other gases, during storage of acidified and untreated pig slurry. J. Appl. Microbiol. 117 (1), 160–172. https://doi.org/10.1111/jam.12498.

Petersen, S.O., Hutchings, N.J., Hafner, S.D., Sommer, S.G., Hjorth, M., Jonassen, K.E.N., 2016. Ammonia abatement by slurry acidification: A pilot-scale study of three finishing pig production periods. Agr Ecosyst Environ 216, 258–268. https://doi.org/10.1016/j.agee.2015.09.042.

Philippe, F.X., Nicks, B., 2015. Review on greenhouse gas emissions from pig houses: Production of carbon dioxide, methane and nitrous oxide by animals and manure. Agr. Ecosyst. Environ. 199, 10–25. https://doi.org/10.1016/j.agee.2014.08.015.

Reisinger, A., Clark, H., Cowie, A.L., Emmet-Booth, J., Fischer, C.G., Herrero, M., Howden, M., Leahy, S., 2021. How necessary and feasible are reductions of methane emissions from livestock to support stringent temperature goals? Philos. Trans. Royal Soc. a-Mathem. Phys. Eng. Sci. 379 (2210). 10.1098/rsta.2020.0452.

Safley, L.M., & Westerman, P.W., 1994. Low-Temperature Digestion of Dairy and Swine Manure. Bioresour. Technol., 47, 2, 165–171. https://doi.org/10.1016/0960-8524(94)90116-3.

Saha, C.K., Zhang, G.Q., Kai, P., Bjerg, B., 2010. Effects of a partial pit ventilation system on indoor air quality and ammonia emission from a fattening pig room. Biosyst. Eng. 105 (3), 279–287. https://doi.org/10.1016/j.biosystemseng.2009.11.006.

Shin, S.R., Im, S., Mostafa, A., Lee, M.K., Yun, Y.M., Oh, S.E., Kim, D.H., 2019. Effects of pig slurry acidification on methane emissions during storage and subsequent biogas production. Water Res. 152, 234–240. https://doi.org/10.1016/j.watres.2019.01.005.

Skovsgaard, L., Jacobsen, H.K., 2017. Economies of scale in biogas production and the significance of flexible regulation. Energy Policy 101, 77–89. https://doi.org/10.1016/j.enpol.2016.11.021.

Sokolov, V., VanderZaag, A., Habtewold, J., Dunfield, K., Tambong, J.T., Wagner-Riddle, C., Venkiteswaran, J.J., Gordon, R., 2020. Acidification of Residual Manure in Liquid Dairy Manure Storages and Its Effect on Greenhouse Gas Emissions. Front. Sustain. Food Syst. 4. 10.3389/fsufs.2020.568648.

Sommer, S.G., Christensen, B.T., Nielsen, N.E., Schjorring, J.K., 1993. Ammonia Volatilization during Storage of Cattle and Pig Slurry - Effect of Surface Cover. J. Agric. Sci., 121, 63–71. https://doi.org/10.1017/S0021859600076802.

Sommer, S.G., Webb, J., Hutchings, N.D., 2019. New Emission Factors for Calculation of Ammonia Volatilization From European Livestock Manure Management Systems. Front. Sustain. Food Syst. 3. 10.3389/fsufs.2019.00101.

Van der Stelt, B., Temminghoff, E.J.M., Van Vliet, P.C.J., Van Riemsdijk, W.H., 2007. Volatilization of ammonia from manure as affected by manure additives, temperature and mixing. Bioresour. Technol. 98 (18), 3449–3455. https://doi.org/10.1016/j.biortech.2006.11.004.

Varma, V.S., Parajuli, R., Scott, E., Canter, T., Lim, T.T., Popp, J., Thoma, G., 2021. Dairy and swine manure management-Challenges and perspectives for sustainable treatment technology. Sci. Total Environ. 778 https://doi.org/10.1016/j.scitotenv.2021.146319.

Webb, J., Menzi, H., Pain, B.F., Misselbrook, T.H., Dammgen, U., Hendriks, H., Dohler, H., 2005. Managing ammonia emissions from livestock production in Europe. Environ. Pollut. 135 (3), 399–406. https://doi.org/10.1016/j.envpol.2004.11.013.

Ye, Z., Zhang, G., Li, B., Strom, J. S., & Dahl, P.J., 2008. Ammonia Emissions Affected by Airflow in a Model Pig House: Effects of Ventilation Rate, Floor Slat Opening, and Headspace Height in a Manure Storage Pit. Trans. Asabe, 51, 6, 2113–2122. https://doi.org/10.13031/2013.25393.