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Research Paper

Covering reduces emissions of ammonia, methane, and nitrous oxide from stockpiled broiler litter

Jesper N. Kamp [*], Anders Feilberg

Department of Biological and Chemical Engineering, Aarhus University, Aarhus, Denmark

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ABSTRACT

Poultry litter, a mix of excreta, bedding material, and discarded feed, is extracted from poultry houses, and used as fertiliser. The litter is often stored in stockpiles outside before field application thereby posing a risk for negative environmental and climatic impact from emissions of ammonia (NH_3) and greenhouse gases (GHG). This study investigated the emissions of methane (CH_4), NH_3, and nitrous oxide (N_2O) from a 22 tonnes broiler litter stockpile over 44 days. The emissions were measured on a farm-scale stockpile with and without coverage using the backward Lagrangian Stochastic method. The results showed distinct emission patterns for each gas during the measurement periods. For all compounds, the emissions during the covered period were significantly lower than during the two uncovered periods. The reduction due to coverage was 92–95% for NH_3, 25–40% for CH_4, and 82–89% for N_2O. NH_3 emissions were highest immediately after coverage removal and during stockpile removal. CH_4 emissions were highest during stockpile removal and lowest during coverage. N_2O emissions were lowest during coverage but a notable increase after coverage removal was observed. The temperature within the stockpile showed variations at different heights, with the highest temperatures recorded in the middle of the stockpile. GHG emissions, based on global warming potential, indicate substantial contributions from N_2O, accounting for 55–72% of emissions in CO_2-equivalents during uncovered periods and 27% during coverage. Furthermore, GHG emissions were reduced 63–72% during coverage compared to the uncovered periods highlighting the importance for immediate coverage of stockpiles to minimise NH_3 and GHG emissions.

Science4Impact statement: The findings of this study offer clear, actionable insights for poultry farm operators and environmental regulators seeking to reduce harmful emissions from broiler litter stockpiles. This reduction not only limits the environmental impact but also minimizes nutrient losses.

For farm operators, implementing immediate and continuous coverage of stockpiles can be an efficient, cost-effective strategy to comply with environmental regulations and reduce greenhouse gas emissions. For policymakers, these results provide a basis to recommend or enforce stockpile covering as a best practice for mitigating agricultural emissions, contributing to climate action and improved air quality.

1. Introduction

Nomenclature	
bLS	backward Lagrangian Stochastic
CO_2-eq	Carbon dioxide equivalent
C	Concentration (μg m^{-3})
C_0	Kolmogorov constant
CE_{bLS}	Concentration-to-emission ratio (s m^{-1})
CH_4	Methane
CRDS	Cavity ring-down spectroscopy
E	Emission (μg m^{-2} s^{-1})
GHGs	Greenhouse gasses
GWP	Global warming potential
L	Obukhov length (m)
MOST	Monin-Obukhov Similarity Theory
N	Nitrogen
NH_3	Ammonia
N_2O	Nitrous oxide
ppb	Parts per billion
ppm	Parts per million
PTFE	Polytetrafluoroethylene
SEM	Standard error of the mean

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* Corresponding author. Blicher Allé 20, 8830, Tjele, Denmark.
E-mail address: jk@bce.au.dk (J.N. Kamp).

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Nomenclature	
TAN	Total ammoniacal nitrogen
TN	Total nitrogen
TS	Dry matter
u_*	Friction velocity (m s^{-1})
VS	Volatile solids
yr	Year
z_0	Roughness length (m)
σ	Standard deviation

Emissions from the agricultural sector have an impact on human health, biodiversity, water quality, soil health, and air composition, surpassing the environmental footprint of many other human activities (Aneja, Schlesinger, & Erisman, 2009; Wyer, Kelleghan, Blanes-vidal, Schauberger, & Curran, 2022). Key environmental and climatic issues arising from agriculture include the emission of ammonia (NH_3) and greenhouse gases (GHGs) nitrous oxide (N_2O) and methane (CH_4) (Aneja et al., 2009). In total, agriculture contributes to over 80% of NH_3 emissions worldwide (Wyer et al., 2022). Manure management is a primary source of NH_3 and N_2O emissions, while for CH_4 emissions, only enteric production in cattle exceeds that from manure management (Gerber et al., 2013). Hence, the storage of animal manure presents a significant environmental challenge within the agricultural sector, contributing to both environmental and climatic concerns.

Despite the negative impact of manure management on climate and the local environment through the release of GHGs and NH_3, the agricultural sector relies heavily on the fertilising value of the manure (Houlton et al., 2019). This value is very important for enhancing crop yield and ensuring sufficient food supply for the growing global population (Uwizeye et al., 2020). Thus, it is also in the farmers' best interest to keep nutrients in the manure making it available after application to maximise crop yield.

Manure is collected in various forms, including solid manure, deep litter (a mixture of excreta and bedding), or slurry (liquid manure). The manure is stored using different storage methods, e.g., tanks, lagoons, and stockpiles. Storage of solid manure and deep litter in stockpiles in fields is a common practice and storage can extend to several months before field application. In Denmark (2022) approximately 40% of non-dairy cattle is housed in systems with solid manure or deep litter, which is similar to the IPCC 2006 distribution (Nielsen, Plejdrup, Winther, Nielsen, et al., 2022). Emissions from storage of solid manure is minimised by field application directly from the housing (Nielsen, Plejdrup, Winther, Mikkelsen, et al., 2022) while the remaining part is stored in stockpiles before field application, thus there is a potential for loss of nutrients and emissions of NH_3 and GHG depending on the storage strategy.

In Denmark, the ammonia emissions from broiler manure management has been constant since 2015 at approximately 0.88 kt NH_3 per year (Nielsen, Plejdrup, Winther, Mikkelsen, et al., 2022). It is estimated that there are 22 million poultry in Denmark in 2022, which is an increase from the 17 to 18 million poultry in 2015 and 2016 (FAOSTAT, 2024). In Europe the number of poultry is estimated at 2.5 billion in 2022 and has been relatively constant for the previous 6 year (FAOSTAT, 2024). It is estimated that there are more than 26 billion poultry worldwide in 2022 of which 60% are in Asia, 21% in the Americas, and 10% in Europe (FAOSTAT, 2024). Poultry production is increasing rapidly, particularly in developing countries and the increase is expected to continue to increase due to increased food demand from a growing population (Mottet & Tempio, 2017). Model estimations predict global annual NH_3 emissions of 5.5 ± 1.2 Tg N yr^{-1} from chicken farming or approximately 13% agricultural NH_3 emissions of which 2.0 Tg N yr^{-1} is emitted from during housing and storage (Jiang, Stevenson, Uwizeye, Tempio, & Sutton, 2021). Hence, there is a huge potential for mitigating emissions from manure management in the poultry sector.

Poultry manure is solid, and it is stored outdoors for varying periods and under varying conditions. Covering stockpiles with a tight-fitting plastic cover has proven to be an efficient way to decrease NH_3 emissions (Chadwick, 2005; Hansen, Henriksen, & Sommer, 2006; Lemes, Nyord, Feilberg, & Kamp, 2023). Covering reduces the air exchange between the stockpile surface and the air, which limits NH_3 emissions that is controlled by the surface exchange. According to a meta-analysis including small-scale piles, which adds uncertainty to the estimates, covering does not have a significant effect on CH_4 emissions but reduces NH_3 emissions by 61% (Pardo, Moral, Aguilera, & delPrado, 2015). Other studies found a higher reduction of NH_3 for covering with 90% for cattle manure (Chadwick, 2005), 90% for broiler deep litter (Sagoo et al., 2007), 88% for layer-hen manure (Naylor et al., 2016) and 92% for cattle deep litter (Lemes, Nyord, et al., 2023). None of these studies found that covering had a significant effect on CH_4 emissions, but a loose cover reduced CH_4 emissions by 50% and NH_3 emissions by 67% (Lemes, Nyord, et al., 2023).

Poultry litter is a source of N_2O emissions, but few studies quantify the emissions from storage (Kebreab, Clark, Wagner-Riddle, & France, 2006) and there is a knowledge gap concerning the effects of mitigation strategies on GHG emissions. In attempts to investigate the effect of coverage on stockpiled layer-hen manure, N_2O emissions were observed to be below the detection limit for uncovered and covered storage in both a laboratory study (Rosa, Arriaga, & Merino, 2022) and a farm scale study (Naylor et al., 2016). Rosa et al. (2022) reported a detection limit for the concentration measurements of 0.2 ppm for NH_3 and 0.03 ppm for N_2O using a photoacoustic multi-gas analyser. However, interferences have been reported for this analyser (Liu et al., 2020). Naylor et al. (2016) used an open path FTIR instrument with precision of 5 ppb for CH_4, 1 ppb for NH_3, and 0.6 ppb for N_2O.

The internal stockpile temperature, which will influence emissions, can rise significantly (Clemens, Trimborn, Weiland, & Amon, 2006; Lemes, Nyord, et al., 2023). It is expected that a certain stack size is needed to achieve representative temperature developments. In a small-scale study, stack height (10–40 cm) was observed to influence the emissions of CO_2, CH_4, and N_2O (Dong, Zhu, Zhou, Xin, & Chen, 2011). Thus, relying on small-scale stockpiles or laboratory studies to examine emissions may introduce bias, as the temperature and emissions in these smaller piles likely deviate substantially from full-scale. Investigating emissions from full-scale stockpiles on the other hand poses practical and technical challenges, and only a limited number of studies have been conducted on a scale that accurately reflects real-world practice.

Emissions from farm-scale stockpiles have been investigated previously in a few studies using micrometeorological methods for determining absolute emissions (Bai et al., 2020; Brown, Wagner-Riddle, & Thurtell, 2002; Lemes, Nyord, et al., 2023). The backward Lagrangian Stochastic (bLS) method has been used to measure emissions of NH_3, N_2O, and CH_4 in high time resolution from stockpiles (Bai et al., 2020; Lemes, Nyord, et al., 2023). However, to our knowledge, no studies have investigated full-scale stockpiles of manure or deep litter from poultry with micrometeorological methods. Consequently, there is a need for investigations of emissions from full-scale stockpiles to accurately determine emission factors of NH_3 and GHGs.

In the present study, the micrometeorological method bLS was used to measure emissions of NH_3 and GHGs from stockpiled broiler deep litter. Emissions were measured continuously in high time resolution from building the stockpile until removal. Conducting measurements on a single pile provided comprehensive data coverage, allowing for the observation of variations and dynamics over time. The stockpile was uncovered the first 6 days and last 10 days, in between the stockpile was covered with a plastic tarp for 28 days. We expect significantly higher NH_3 emissions in the uncovered period. We expect that CH_4 emissions will be constant throughout the experiment. Finally, we expect that N_2O emissions will be indistinguishable from background levels.

2. Materials and methods

2.1. Broiler house

The deep litter was collected from a broiler chicken production facility with two houses of approximately 2000 m^2 and holding 33,500 broilers each in a production cycle. The broilers were of the type Rustic Gold with a target weight of 2150 g over the 42 days production cycle. The expected growth was 1 kg per 1.67 kg of feed that was a mix of soy and wheat with minerals and vitamins. Water was available ad libitum. The litter material used was sphagnum mixed with planed wood chips. The broiler house was operated to keep the litter dry to avoid burns on broilers' feet and hocks.

The deep litter was scraped together and transferred to a trailer immediately after the broilers were sent to the slaughterhouse. Two truckloads were used to build the stockpile and approximately 2 h after the broilers were collected, the stockpile was built in the field.

2.2. Stockpile

The measurements were conducted in an open field at Aarhus University, Campus Viborg, with stubble of 20 cm height after winter wheat was harvested the week prior to the experiment. The total storage period was 44 days. The stockpile was built on August 29, 2023, in a trapezoid shape with an initial height of approximately 1.8 m and an initial weight of 22.0 tonnes. Just before removal on October 12, 2023, the stockpile had an approximate height of 1.3 m and a weight of 22.6 tonnes. The length and width were approximately 8.0 m and 4.5 m, respectively, giving an area of approximately 36 m^2.

The stockpile was uncovered for the first 6 days before it was covered with a black plastic sheet (polyethylene) with a thickness of 0.14 mm (MegaplastPower, Compex, Denmark). The plastic covered the entire stockpile, forming an airtight and watertight barrier. It was held down by tires and sandbags as is the normal practice in Denmark. The plastic was removed again 10 days before the experiment ended to determine if there was an emission potential during the covered period and if the emissions were at the same level during the two uncovered periods.

To estimate leaching, three 40 L buckets with holes in the lid were dogged into the ground before the stockpile was built. The lids were glued to a plywood plate to avoid the buckets being filled with manure. A silicon ring was glued to the top of the plywood plate for water to be able to run into the bucket. However, there was no liquid in the buckets when the stockpile was removed, thus leaching could not be quantified.

Temperature sensors (HOBO MX Pendant, Onset Computer Corporation, MA, USA) were placed at three different positions and three different heights in the stockpile. Sensors were at ground level, 1 m above the ground, and directly under the plastic cover at the top of the stockpile. During the two uncovered periods, the sensors were positioned on top of the pile.

2.3. Chemical analysis

Samples of the unused pure litter material were collected to determine background levels originating from the litter material. All samples were collected by taking spot samples at a minimum of 8 different locations to obtain representative samples. Samples were collected in 0.5 L plastic containers and stored at −18 °C before analysis. Three samples were collected both before and after the storage period. Duplicate analyses of each sample were conducted to determine dry matter content (TS), volatile solids (VS), total nitrogen (TN), and total ammoniacal nitrogen (TAN) (APHA, 1999) (Table 1).

2.4. Emission measurements and instruments

The emission measurements were conducted using the backward Lagrangian Stochastic (bLS) model (Flesch, Wilson, & Yee, 1995), which models the transport of air based on the atmospheric conditions backwards in time. The R software package bLSmodelR (https://github.com/ChHaeni/bLSmodelR, v4.10 (Häni, Flechard, Neftel, Sintermann, & Kupper, 2018),) was used to determine emissions in half hour intervals as recommended by Flesch, Wilson, Harper, Crenna, and Sharpe (2004). An assumption for the model is a flat and homogeneous emitting surface, which was also assumed in this study, but the emission (E) from an elevated source can also be determined.

$$E = \frac{C_{downwind} - C_{upwind}}{CE_{bLS}} \tag{1}$$

In Eq. (1), C_{downwind} and C_{upwind} are the measured concentration downwind and upwind from the source, respectively. An output of the model is the concentration-to-emission ratio (CE_{bLS}) that is determined specifically for a source depending on the exact location of sensors and source and the turbulence characteristics parameterised using the Monin-Obukhov Similarity Theory (MOST). The inputs to the model are source and sensor position, wind direction, friction velocity (u_*), and atmospheric stability among others. In each half hour interval, 500,000 trajectories were simulated backward in time and the trajectories touching the ground inside the source were used to determine the concentration-to-emission ratio, see Häni et al. (2018) for a detailed explanation. Filtering ensures that only high accuracy data is included because the bLS model is influenced by atmospheric conditions (Flesch et al., 2004). Intervals were removed when either of the following filtering criteria was met friction velocity (u_*) < 0.05 m s^{-1}, stability in form of the Obukhov length ($|L|$) < 2 m, roughness length (z_0) > 0.1 m, the standard deviation of the along wind divided by u_* (σ_u/u_*) > 4.5, standard deviation of the crosswind divided by u_* (σ_v/u_*) > 4.5, or Kolmogorov constant (C_0) > 10 (Bühler et al., 2021). Furthermore, intervals, when less than 10% of the released trajectories had touchdown inside the source area, were also removed to ensure that the measured concentration increase was due to emissions from the stockpile. Applying the quality criteria removed 59.5% of the data giving 859 half hour intervals with valid data.

An ultrasonic anemometer (WindMaster, Gill, Hampshire, UK) measured the three wind components at 16 Hz time resolution at 2 m, which were used to calculate wind speed and direction, friction velocity (u_*), and atmospheric stability with the Monin-Obukhov length (L). A GPS (Trimble R10, Sunnyvale, California, USA) was used to measure the positions of the source and sensors.

The up- and downwind concentrations were measured with CRDS instruments (model G2509, Picarro Inc., Santa Clara, CA, USA). The CRDS (model G2509) instrument has been used with the bLS model to determine agricultural emissions from liquid manure storage (Lemes, Garcia, Nyord, Feilberg, & Kamp, 2022) and proven to be a reliable instrument in agricultural environments (Garcia, Støckler, Feilberg, & Kamp, 2024). The downwind concentration was measured with a

Table 1
Characteristics of the pure litter material and the stockpiled broiler litter at the beginning and end of the experiment. The standard deviation is indicated with ± and the number of replicates is indicated in parentheses.

	Weight (ton)	Height (m)	TS (%)	VS (%)	TN (g^{-1} kg^{-1})	TAN (g^{-1} kg^{-1})
Pure litter	–	–	62.2 ± 2.1 (2)	97.9 ± 0.3 (2)	3.6 ± 0.5 (2)	0.3 ± 0.02 (3)
Start storage	22.0	1.8	51.2 ± 7.8 (6)	86.9 ± 0.7 (6)	25.7 ± 3.5 (6)	5.4 ± 0.7 (6)
End storage	22.6	1.3	52.5 ± 4.9 (6)	81.2 ± 7.9 (6)	28.9 ± 3.6 (6)	6.6 ± 0.8 (6)

sampling line measuring at seven discrete positions through critical orifices that ensure an even flow through each of the seven orifices. Using a sampling line rather than single-point sampling increases the range of wind directions at which the plume from the source is measured thereby increasing the data coverage. Furthermore, the sampling line was moved around the pile to capture the plume from the pile as much as possible. The experiment lasted 44 days during which the sampling line had 11 different positions in the field (Fig. 1). In the period with north-westly winds, the background measurement position was moved towards west or otherwise located directly south of the pile (Fig. 1). Each of the locations were determined used a GPS. The distance between the sampling line and the stockpile should be minimum 10 times the height of the stockpile according to Harper, Denmead, and Flesch (2011) and in this experiment the distance was between 16 m and 23 m (Fig. 1).

The line was 12 m long and consisted of polytetrafluoroethylene (PTFE) tubing that was heated to approximately 80 °C using heating wire and there were 2 m between each orifice that was also heated to approximately 80 °C and placed approximately 1.8 m above ground. The sampling line has been evaluated and validated using the bLS model with a release of known quantities of ammonia and methane (Lemes, Häni, Kamp, & Feilberg, 2023). The recovery rate for methane was 95 ± 8%, whereas ammonia was 82 ± 5% for this sampling line. The upwind concentration was measured at a single point at 1.5 m through a PTFE sampling line heated to approximately 60 °C.

The climate impact was assessed using the global warming potential (GWP) over 100 years for N_2O (273) and CH_4 (non-fossil: 27.0) (IPCC, 2023). Furthermore, the indirect N_2O emissions from NH_3 volatilisation was also included using the IPCC default at 0.01 kg N_2O-N per kg NH_3-N volatilised (IPCC, 2019).

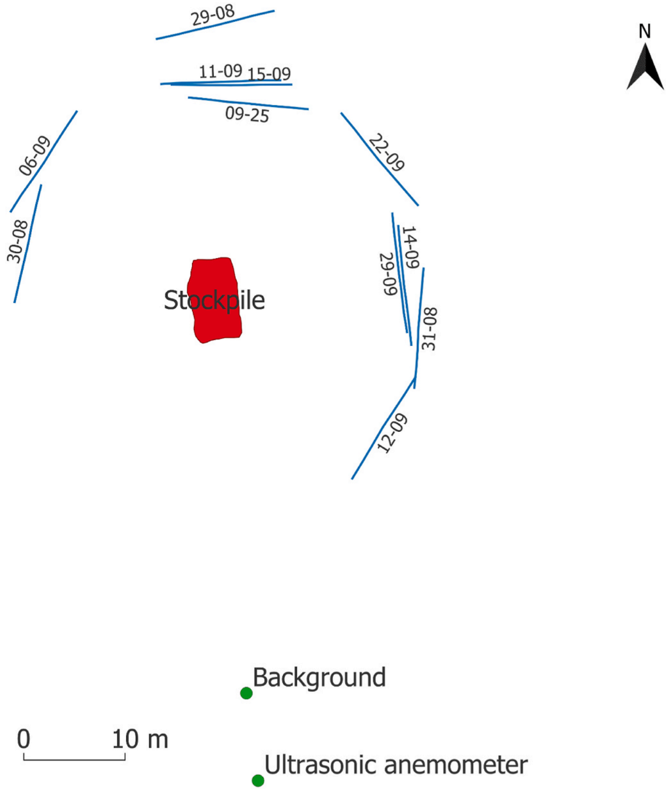

Fig. 1. Overview of field with the stockpile in red. The blue lines denote the position of the sampling line with the dates marking the starting day of the measurement for that specific location. The positions of the background concentration measurement and the ultrasonic anemometer are shown in green. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.5. Data analysis

A two-sample *t*-test was used to compare the mean values of the chemical analysis results of the litter before and after storage. For measured emission, the use of multiple measurements on a single experimental unit (one stockpile) precluded conventional hypothesis testing. It has been argued that conducting a formal statistical analysis becomes redundant when visual evidence is unequivocal, as it would not enhance the credibility of the visual evidence (McDowall, McCleary, & Bartos, 2019; Parsonson & Baer, 1986). Time series analysis tools could be used to make inferences about a single experimental unit (McDowall et al., 2019), but here a more straightforward graphical approach was used (Parsonson & Baer, 1986). Plots of emission rate over time showing covering and uncovered events were visually assessed for changes that occurred immediately after an event and consistent shifts in emission level. Effect size was estimated from mean values that were calculated for each period. MATLAB 2023b (The MathWorks Inc., 2023) was used for all data analysis and plotting of the data besides running the bLSmodelR.

3. Results and discussion

3.1. Emissions

The emissions of CH_4, NH_3, and N_2O were measured over 44 days (Fig. 2). The emissions of NH_3 were highest immediately after the coverage was removed and during the short period when the stockpile was removed. The average emissions of CH_4, NH_3, and N_2O during the longer periods without and with the plastic cover were different from each other (Table 2) and the lowest emissions were observed during the covered period. There was no clear diurnal variation of the emissions, however, a few high emissions of NH_3 and N_2O were observed during the daytime, whereas no patterns were clear for CH_4. The wind is generally more calm at night, which can explain the higher emissions of NH_3 during daytime as normally NH_3 emissions increase with increasing wind speed (Kamp, Häni, Nyord, Feilberg, & Sørensen, 2021). Furthermore, lower surface temperature at night decrease NH_3 emissions as dissociation and evaporation is lower with lower temperatures (Hafner, Kamp, & Pedersen, 2024).

For CH_4, the highest emissions were also observed during the period when the stockpile was removed from the field and lowest emissions were observed during the period with covering established. The average emissions from the three periods were different (Table 2) but overall, the emissions were low with both positive and negative emissions, which indicate emissions close to zero.

The N_2O emissions were small in most intervals, especially during the period with coverage. After a few days delay, there was a clear increase in N_2O emissions during the first uncovered period. There was a high increase in emissions immediately after the coverage was removed, like for NH_3, which is most likely caused by a release of the gas captured inside the cover. The average emissions during the two uncovered periods were higher than the covered period (Table 2).

Lower emissions were observed during coverage for NH_3 (92–95%), CH_4 (25–40%), and N_2O (82–89%). The observed reduction due to covering for NH_3 is consistent with previous results from broiler litter that showed a reduction of 90% by covering (Sagoo et al., 2007) and also consistent with results from cattle manure (Chadwick, 2005) and cattle deep litter (Lemes, Nyord, et al., 2023) that showed reductions of 90–92%.

As expected, the emissions were higher during the uncovered period for NH_3 because the emissions are controlled by the air-side resistance (Pardo et al., 2015). The plastic act as a physical barrier that blocks air movement over the surface limiting NH_3 emissions from the surface. At the same time, a plastic barrier will limit oxygen availability at the surface. The oxygen level in the stockpile potentially influences both CH_4 oxidation and N_2O formation at or close to the surface, thus it can be

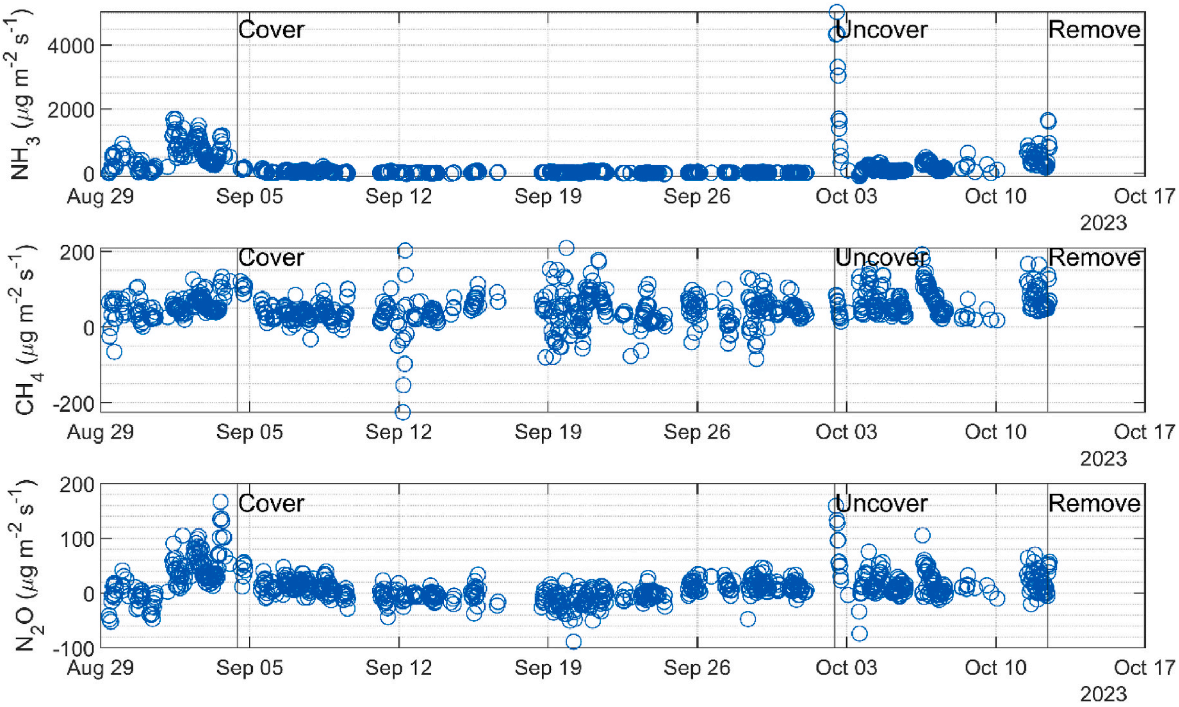

Fig. 2. Emissions of CH_4, NH_3, and N_2O from a stockpile with broiler litter in half hour measurement intervals. The pile was uncovered in the first 6 days and last 10 days as indicated by the vertical lines.

Table 2

Emissions of CH_4, NH_3, and N_2O from a stockpile with broiler litter during different storage phases. n is the number of half hour intervals, Avg ±SD is the average emission ± the standard deviation in $\mu g\ m^{-2}\ s^{-1}$, SEM is the standard error of the mean, and l95 and u95 is the lower and upper 95% confidence bounds.

Periods	n	Avg ±SD	SEM	l95	u95
CH_4 μg m^{-2} s^{-1}					
Uncovered	144	54.3 ± 28	2.3	49.8	58.9
Covered	507	40.9 ± 41	1.8	37.3	44.4
Uncovered	203	68.2 ± 35	2.5	63.4	73.1
Removal	5	93.5 ± 36	16.3	48.2	138.8
NH_3 μg m^{-2} s^{-1}					
Uncovered	144	591.1 ± 398	33.2	525.4	656.7
Covered	507	26.6 ± 33	1.4	23.8	29.5
Uncovered	203	336.8 ± 645	45.3	247.5	426.0
Removal	5	1164.0 ± 431	192.6	629.4	1698.7
N_2O μg m^{-2} s^{-1}					
Uncovered	144	32.5 ± 39	3.3	26.1	39.0
Covered	507	3.5 ± 17	0.8	2.0	4.9
Uncovered	203	19.0 ± 26	1.8	15.3	22.6
Removal	5	49.5 ± 7	3.2	40.7	58.3

expected that covering influences the emissions (Hansen et al., 2006). In addition, the temperature increase is driven by aerobic processes and therefore influenced by oxygen availability. CH_4 production takes place in anaerobic environment, but Chadwick (2005) found that covering farmyard manure could either increase or decrease CH_4 emissions during different periods. This most likely reflects the counteracting effects on CH_4 that covering can have due to changes in temperature and oxygen availability, respectively. Other studies found that covering did not significantly affect the CH_4 emissions (Lemes, Nyord, et al., 2023; Pardo et al., 2015) and, thus, it was not expected that CH_4 emissions were also reduced by the coverage in this study. N_2O is mainly expected to be produced under anaerobic conditions by denitrification of nitrate, which in turn is produced by nitrification and nitrite oxidation under aerobic conditions (Pardo et al., 2015). Formation of N_2O therefore typically takes place near a transition zone between anaerobic and aerobic conditions (Pardo et al., 2015). Since nitrification is limited under anaerobic conditions (Shah et al., 2016), it is possibly that covering could limit N_2O emissions, which was indeed observed in the present study. Previously, quantification of N_2O emissions has not been possible due to low concentration differences between up- and downwind measurement positions (Lemes, Nyord, et al., 2023) or measurements below detection limits (Naylor et al., 2016; Rosa et al., 2022).

3.2. *Temperature*

The temperature patterns inside the stockpile measured at three different heights differed, but unfortunately, all three sensors at the middle height malfunctioned before the end of the experiment (Fig. 3). The highest temperatures were measured in the middle of the stockpile at 56.5 °C. The temperature in the middle of the pile increased rapidly after it was built whereas the bottom temperature only increased slightly and slowly over time (Fig. 3). The temperature at the bottom of the stockpile was relatively stable, ranging from 20 °C to 29 °C, whereas the temperature at the top of the stockpile had a clear diurnal pattern that coincided with the ambient air temperature (Fig. 3). The temperature at the top of the stockpile increased rapidly immediately after coverage (+~20 °C) and the maximum temperature was observed in the following days at 54.4 °C at the top of the stockpile. The temperature at the top of the stockpile decreased around September 12 and 19, which coincided with rainfall on these two days (Fig. 4).

Oxygen availability can potentially reduce CH_4 emissions via microbial methane oxidation, but can also increase emissions due to temperature increases caused by aerobic degradation of organic material (Chadwick et al., 2011). It is suggested that covering a stockpile with an air-tight cover will limit the activity of aerobic microorganisms and the associated temperature increase, which would have stimulated CH_4 emissions from anaerobic microenvironments deeper in the stockpile (Chadwick et al., 2011). In this experiment, the temperature in the middle of the stockpile continued to increase several days after coverage, but then started to decrease after one week of coverage (Fig. 3). This decrease might be related to the development of anaerobic

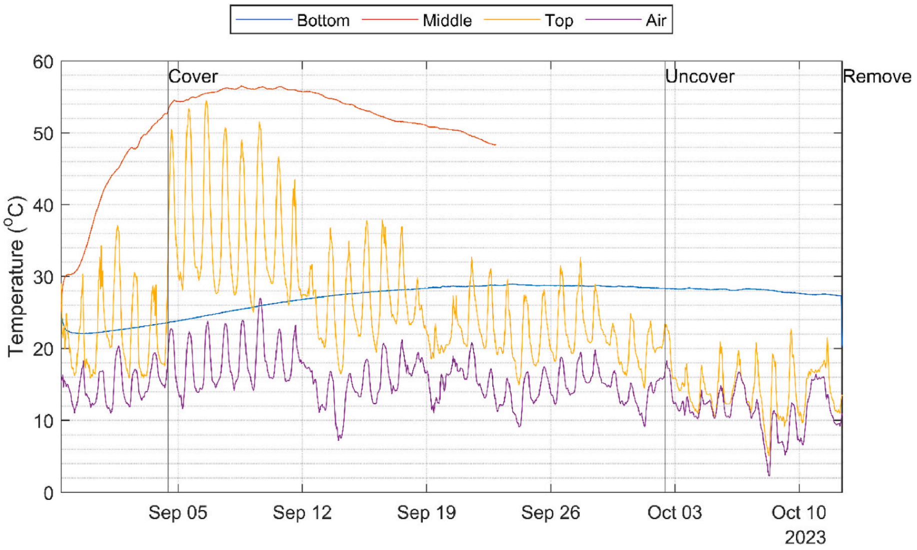

Fig. 3. Temperature measured inside the stockpile at the bottom, 1 m above the bottom (middle), and on the top of the stockpile along with the air temperature measured at 2 m.

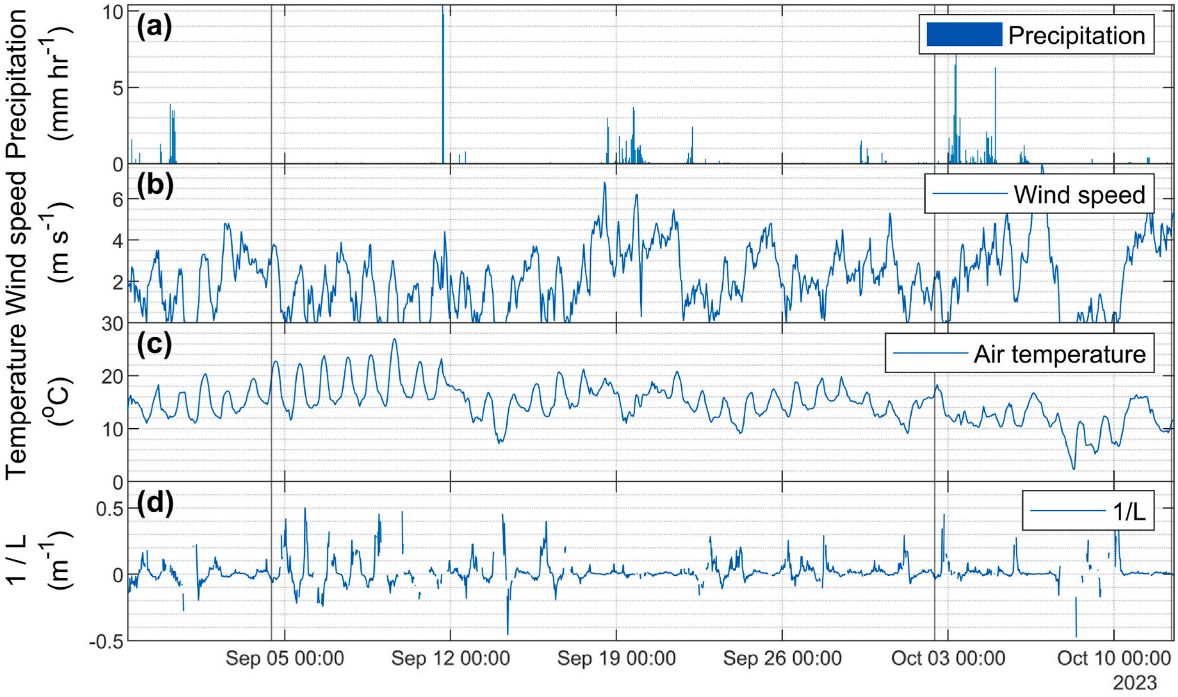

Fig. 4. Ambient conditions during the measurements. a) Precipitation (mm hr^{-1}), b) wind speed (m s^{-1}), c) temperature (°C), and d) atmospheric stability measured as the inverse Monin-Obukhov length (L) (m^{-1}).

conditions after all available oxygen underneath the cover had been consumed. Similar observations were also seen by Lemes, Nyord, et al. (2023) that observed lower temperature inside covered stockpiles compared to uncovered or incompletely covered stockpiles. Sagoo et al. (2007) observed a rapid increase in temperature for the first week of storage and elevated temperatures throughout 6 months of storage, but with ~10 °C lower temperature in the covered stockpile compared to a conventional stockpile. The uncovered periods in this experiment were too short to draw any conclusions on the cause for the temperature patterns during these two periods.

3.3. Precipitation

During the 44 days of measurements, the total amount of precipitation was 141.3 mm of which 21.8 mm and 55.8 mm fell during the two uncovered periods. The mass of the stockpile increased by approximately 600 kg during the experiment probably due to increased water concentration. However, this is not reflected in the analysis of the manure as the end of storage dry matter content was 1.3% higher than at the beginning indicating water loss from the pile, but the means were not significantly different (Table 1). This discrepancy between measured dry matter and weight is most likely due to manure sampling as it is very difficult to take truly representative samples from a large heterogenous stockpile.

It has previously been suggested that rainfall induce anaerobic conditions that increase N_2O emissions (Bai et al., 2020). In this study, the lowest fluxes were measured during or directly after rainfall during the uncovered periods. Negative fluxes were measured during the rainfall in the morning on August 31 (17 mm precipitation, 3:00–10:00) followed by positive fluxes from 9:00 on September 1 until the pile was covered. Similarly, the rainfall on October 3 (28.5 mm precipitation, 1:00–13:00) was followed by increased N_2O emissions with a few hours delay. This could indicate that increased N_2O emissions occur with some delay after the rain event. The results correspond qualitatively well with observations of the effect of rain on N_2O formation in manure surface crusts (Petersen, Dorno, Lindholst, Feilberg, & Eriksen, 2013).

On the other hand, keeping conditions relatively anaerobic by e.g., covering or compacting has been proposed as a potential mitigation method for N_2O (Chadwick et al., 2011), which can explain the low N_2O emissions during the covered period in this study. Additionally, the pile was compacted naturally during the experiment and the height of the pile decreased from approximately 1.8 m to 1.3 m from establishment until removal. This could lead to lower porosity and more anaerobic conditions, which could well explain lower N_2O emissions during the second uncovered period compared to the first uncovered period (Table 2). This contrasts with an expected higher moisture level in the second uncovered period that is expected to support a higher production of N_2O (Thorman, Chadwick, Harrison, Boyles, & Matthews, 2007). The broiler litter had a high dry matter content (51.2%) compared to cattle and pig farmyard manure that normally has a dry matter content of 20–25% at the beginning of the storage period (Lemes, Nyord, et al., 2023; Thorman et al., 2007). Few studies have investigated broiler litter, so comparisons are often drawn with cattle and pig farmyard manure. However, the higher moisture content in cattle and pig manure can more extensively promote nitrification and the formation of a nitrate source for denitrification compared to broiler litter (Thorman et al., 2007). This will inevitably cause differences in comparisons of emissions from different sources.

3.4. Leaching

Previous studies have reported 16–32% leaching loss from uncovered cattle manure (Shah et al., 2016), but only 2.9% from covered broiler litter (Sagoo et al., 2007). It was attempted to quantify leaching by submerging buckets into the ground underneath the stockpile at three different locations to collect any liquid going into the ground from the pile. However, there was no liquid in the buckets after the storage period even though there was nearly 88 mm of precipitation during the two uncovered periods. This means that it was not possible to quantify leaching in this study. The absence of significant leaching can be explained by the initially high dry matter content of the broiler litter, which apparently could absorb the precipitated water.

3.5. Total emissions and climate impact

The climatic impact of the covered and uncovered periods was assessed using the GWP over 100 years for N_2O (273) and CH_4 (non-fossil: 27.0) (IPCC, 2023) and the indirect N_2O emissions from volatilised NH_3 (IPCC, 2019). Normally, N_2O emissions from manure storage are small compared to CH_4 emissions, especially for liquid manure (Kupper et al., 2020), but Bai et al. (2020) found that a stockpile with cattle manure had equal contributions from N_2O and CH_4. In the present study, N_2O emissions accounted for 64–79% of the emissions in CO_2-equivalents while uncovered and 30% during the coverage period, hence, a large climatic contribution from N_2O (Table 3). In terms of daily GHG emissions in CO_2-equivalents, the daily emissions were reduced by 69–77% during the covered period compared to when uncovered (Table 3). It is important to note that the emission values were lower in the second uncovered period, and it is not expected that the average emissions presented here will be representative for a situation where a pile would be left uncovered for a much longer period, i.e. extrapolation of the uncovered periods should be done only after careful consideration. However, covering immediately after building a stockpile will minimise storage emissions. In this case, an immediate cover would have reduced NH_3 emissions by more than a factor of 20 and GHG emissions by a factor of more than 3. Swift and efficient covering of litter manure piles therefore represents a cheap and simple strategy to achieve immediate and high reduction of emissions from poultry production on a global scale. From a yearly production of poultry meat of 100 million tons, 92% is produced in specialised broiler systems (Mottet & Tempio, 2017), and this simple low-cost strategy therefore has global potential for mitigation of GHG emissions and NH_3. Furthermore, it is implementable in developing countries with high poultry production, such as in Asia where ~60% of the global poultry production takes place (including China) (FAO, 2023; FAOSTAT, 2024).

Table 3

Total emissions during the different storage phases as total mass or fraction of total N at the beginning of the storage and as CO_2-eqivalents using GWP-100 for $N_2O = 273$ and $CH_4 = 27.0$ (IPCC, 2023) including the indirect N_2O emissions from volatilised NH_3.

Period	Uncovered	Covered	Uncovered	Removal	Total
Time (days)	6.0	28.0	10.0	0.1	44.1
NH_3					
Loss (kg NH_3-N)	9.1	1.9	8.6	0.26	19.9
Loss (% of total N)	1.61%	0.34%	1.52%	0.05%	3.52%
N_2O					
Loss (g N_2O-N)	194	96	188	4	482
Loss (% of total N)	0.03%	0.02%	0.03%	0.001%	0.09%
CO_2-eq. (kg/day)	12.9	1.1	7.5	21.5	–
CH_4					
Loss (kg CH_4-C)	0.76	2.66	1.59	0.02	5.03
CO_2-eq. (kg/day)	3.4	2.6	4.3	5.9	–
Total GHG					
CO_2-eq. (kg/day)	16.3	3.7	11.8	27.4	–

Analysis of the deep litter at the beginning and end of the experiment was expected to give insights into the loss of nitrogen during the storage. However, as mentioned in section 3.3, it is very difficult to take representative samples of a heterogenous material like manure. Only the TAN concentration is significantly different before and after storage, while dry matter, total N, and volatile solids were not significantly different. Thus, it was not possible to conduct a mass balance based on amount of total nitrogen before and after the storage. Emissions will be compared to the initial amount of total N in the following. The loss of N as NH_3 and N_2O corresponds to 3.5% and 0.09%, respectively, of the initial total N in the stockpile over the three phases during the 44 measuring days (Table 3). During the two uncovered periods (6 and 10 days) 1.6 and 1.5% of N was lost as NH_3, while the covered period of 28 days only accounted for 0.34% of N loss (Table 3). Time is a relevant factor for these estimates as emissions are expected to continue for a prolonged period, but the emission strength is probably affected, especially if uncovered. This could be suggested based on the current study where emissions were higher in the first compared to the second uncovered period. One possible explanation was the higher surface temperature during the first period. On the other hand, the emissions were constantly low throughout the covered period and increased emissions were observed after the coverage was removed, indicating a remaining potential for NH_3 emissions over longer periods while covered.

Most studies have found higher loss of N_2O than in the present, e.g., pig farmyard manure 2.6% (Thorman et al., 2007), cattle farmyard manure 4.3% (Thorman et al., 2007), cattle manure 1–4% (Shah et al., 2016), and 0.8% (Bai et al., 2020). The differences are most likely due to different manure types, storage length, and storage conditions. The studies listed above measured over 160 days and all were uncovered.

Previous studies have found loss of NH_3 in the same order of magnitude as the present study for uncovered cattle manure 2–9% (Shah et al., 2016) and 5.3% (Bai et al., 2020), covered cattle deep litter

2.9–5.3%, and covered horse deep litter 8.7% (Lemes, Nyord, et al., 2023). In a study with broiler litter, 1.3% of initial total N was lost as NH_3 over the 6 months storage period (Sagoo et al., 2007), which was 0.34% over 28 days while covered in this study. According to Sagoo et al. (2007), 25% of NH_3 was lost during the first month storage, equivalent to 0.325%, which is identical to the loss observed in this study over 28 days. Assuming similar behaviour in the two studies gives the possibility to extrapolate the emissions over longer storage periods, which can be common due to limited timespans where solid manure is field applied.

This observational study is limited to a single experimental unit without case-control treatments or repetitions. This was done deliberately to ensure higher data coverage compared to previous studies with multiple piles (Lemes et al., 2023) in order to monitor the temporal emission patterns in detail. Achieving this for multiple stockpiles is logistically challenging and requires large equipment investments. The findings from this single stockpile may not be directly transferrable to other stockpiles with deep litter produced under different production systems. Additionally, temporal changes such as weather conditions and microbial activity could influence the results independently of the treatments. Despite the high data coverage throughout the measurement periods, with 859 half-hour intervals in total, it cannot be excluded that variations in the environmental factors might have influenced the results. Moreover, although the periods with and without cover were independent, the former treatment might have affected the subsequent treatment.

The results presented here indicate that covering manure piles is a viable strategy for achieving significant global GHG emission reductions at a low cost. This approach warrants further attention, with comprehensive documentation of its effects across various sources and additional repetitions to confirm the findings. Even though a clear decrease in emissions were observed for NH_3, N_2O, and CH_4 in this study there is a need for integrated manure management strategies over the whole manure management chain to avoid swapping emissions from one part of the chain to another.

4. Conclusion

This study provides valuable insights into the emission dynamics of CH_4, NH_3, and N_2O from broiler litter stockpiles. The measured emissions were lower during the covered period for NH_3 (92–95%), CH_4 (25–40%), and N_2O (82–89%). The emissions were highest immediately after the coverage was removed and lowest during the covered period.

In CO_2-equivalents, N_2O emissions accounted for 55–72% of emissions during the uncovered periods and 27% during the covered period with CH_4 accounting for the remaining part. Covering decreased the overall GHG emissions in terms of CO_2-eqivalents with 63–72% during the covered period. The results of this study emphasise the significance of covering manure stockpiles to mitigate NH_3 and GHG emissions and suggests that efficient covering is a cost-efficient strategy for global GHG mitigation.

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Code and data availability

Calculations and data can be found in a GitHub repository (https://github.com/AU-BCE-EE/Kamp-2024-Broiler-Litter).

CRediT authorship contribution statement

Jesper N. Kamp: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Anders Feilberg:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

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.

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