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Methodological factors affecting ammonia emission measurement with flux chambers from field-applied biogas digestate slurry (Technical note)

Johanna Pedersen[a,*], Sasha D. Hafner[a], Andreas S. Pacholski[b]

[a] Aarhus University, Department of Biological and Chemical Engineering, Denmark

[b] Thünen Institute for Climate-Smart Agriculture, Braunschweig, Germany

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ABSTRACT

This study evaluated technical factors influencing relative ammonia emissions following field application of biogas digestate using different slurry spreading methods. Experiments assessed: (i) slurry distribution uniformity across a trailing hose boom, (ii) the influence of driving speed, (iii) effects of hose spacing, and (iv) the effect of relocating dynamic flux chambers during measurement. Across all tests realistic application rates and representative field conditions were ensured. Results demonstrate that careful equipment setup, particularly hose selection and consistent spacing, minimized variability in measured emissions and dynamic flux chamber relocation elevated measured emissions. These findings provide practical guidance for experimental design and emission mitigation under typical farming conditions.

1. Introduction

Field application of organic fertilizers such as slurry and anaerobically digested slurry (digestate) contributes significantly to ammonia (NH_3) emissions (Uwizeye et al., 2020; Yan et al., 2024). To optimize nutrient utilization and minimize environmental pollution, numerous studies have been conducted to evaluate application methods and treatments that can reduce ammonia volatilization in past decades. Accurate measurements are essential for quantifying and validating the effects of such mitigation strategies.

Dynamic chamber methods are widely used for comparative assessments and determination of relative emission reductions (Bussink et al., 1994; Misselbrook et al., 2005; Scotto di Perta et al., 2020). However, several methodological parameters may influence measured emissions. Some of these have rarely been studied and are addressed in the present work.

Because chambers typically cover only a small area, it is crucial that the slurry application within the plot is representative of field conditions. Therefore, it is important to assess variability in slurry distribution over space for application techniques used in the emission trials.

In practical farming, slurry is applied as efficiently as possible without compromising crop yield or machinery performance. In Denmark, slurry tankers equipped with trailing hoses or trailing shoes typically operate at about 12 km h^{-1}, whereas experimental application often occurs at lower speeds (4–5 km h^{-1}) using specialized machinery. Application speed is expected to affect slurry distribution on soil by affecting the area covered with slurry and thereby ammonia emissions, particularly for techniques where contact between the applied slurry and soil plays a key role, such as trailing shoes.

Another factor influencing representativeness and comparability is the spacing between slurry bands. In Denmark, trailing hoses are generally spaced 300 mm apart, whereas trailing shoes are spaced 250 mm apart. To make a comparison of the application technique, and not the banding distance, a uniform spacing is usually chosen in trials. But distance of bands may play a role, because the amount of slurry applied in each band must increase as distance increases for a fixed application rate.

Finally, practices related to chamber placement can also affect results. Some studies have relocated chambers daily to avoid blocking rain (Forrestal et al., 2015) while others have not (Bittman et al., 2005).

In the present study four key but under-investigated aspects relevant to chamber-based ammonia emission measurements were investigated: i) the distribution uniformity of slurry applied by trailing hose and trailing shoe booms, ii) the effect of driving speed on ammonia emissions, iii) the influence of hose spacing on ammonia emissions, and iv) the impact of chamber relocation during the measurement period on ammonia emissions.

* Corresponding author. Aarhus University, Blichers Alle 20, 8830, Tjele, Denmark.
E-mail addresses: jp@bce.au.dk (J. Pedersen), sasha.hafner@bce.au.dk (S.D. Hafner), andreas.pacholski@thuenen.de (A.S. Pacholski).

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Table 1
Digestate properties (mean ± standard deviation, $n = 2$). TAN: total ammoniacal nitrogen.

Trial	Digestate	Dry matter (%)	TAN (g kg^{-1})	Total nitrogen (g kg^{-1})	pH	Application rate (m^3 ha^{-1})	Application rate (kg TAN ha^{-1})
2a	Unseparated	3.35 ± 0.01	1.51 ± 0.07	1.97 ± 0.05	7.7 ± 0.1	32	48
2b	Unseparated	3.74 ± 0.001	1.41 ± 0.03	1.90 ± 0.04	7.9 ± 0.03	32	45
3a	Unseparated	3.70 ± 0.10	1.69 ± 0.004	2.41 ± 0.13	7.5 ± 0.04	35	59
3a	Liquid fraction (separated)	1.73 ± 0.003	1.21 ± 0.18	1.79 ± 0.03	7.9 ± 0.1	35	42
3b	Unseparated	3.48 ± 0.09	1.52 ± 0.03	2.08 ± 0.06	7.7 ± 0.02	35	53
3b	Liquid fraction (separated)	3.00 ± 0.002	1.71 ± 0.08	2.72 ± 0.07	8.0 ± 0.02	35	60
4	Unseparated	3.29 ± 0.003	1.48 ± 0.03	2.29 ± 0.14	7.8 ± 0.01	32	47

Fig. 1. Slurry boom with three different application methods mounted. From left to right: trailing shoe (Bomech, Albergen NL) (section 1), trailing hose (TH, outer diameter: 40 mm) (section 2), trailing shoe (Samson Agro A/S, Viborg, DK) (section 3). For ammonia emission measurements with dynamic flux chambers, the chambers are placed over two slurry bands from the two centered outlets within each section, marked with orange squares. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2. Materials and methods

2.1. Digestates and ammonia chamber measurements

In all trials, the digestates and liquid phase of separated digestates used were obtained from the biogas plant at Campus Viborg, Aarhus University. For trial 3 digestate was separated with a decanter centrifuge (GEA Westfalia Separator, GEA Industry GmbH, LA, USA). Prior to application, digestate samples were collected in the field for laboratory analysis. Digestate pH was measured by a pH metre (Knick Portavo 902 pH meter). Digestate was gravimetrically analysed for dry matter by heating at 105 °C (APHA, 2017). Total nitrogen was analysed by low-field nuclear magnetic resonance spectrometry (Jensen et al., 2021) and total ammoniacal nitrogen was determined photometrically using a commercial kit (Spectroquant Test kit No. 1.00683.0001, Merck KgaA, Darmstadt, Germany) (Table 1).

Ammonia losses were measured using a system of 16 dynamic flux chambers and concentration measurements with cavity ring-down spectrometer (CRDS) (G2103 NH_3 Concentration Analyzer, Picarro, CA, USA). Chamber design, airflow distribution, and system validation are detailed in (Pedersen et al., 2024). Each chamber (0.38 m^2 round base, 700 mm diameter 392 mm height) used a deflector plate to ensure uniform distribution over the soil surface (Figs. S2 and S3). Air was drawn into the chamber from three air-intakes located on top of the chamber with the intake at 1.4 m height above the soil surface. The airflow was maintained at an air exchange rate of 15 min^{-1}. Air from each chamber and three background inlets was drawn through heated PVDF tubing (1.5 L min^{-1}) to a rotary valve and analysed by the CRDS for 8 min per position, with 2-s readings; the final 30 s were averaged and use for calculations of the flux. Measurements were conducted for 160 h, with a measurement for each chamber every 2.5 h. Flux (F) was calculated as $F = (C \cdot q)/A$, with C being the background corrected concentration, q the airflow and A the plot area covered by the chamber. The cumulative emissions was calculated using the trapezoidal rule.

For manually applied digestate (trials 3 and 4), digestate was applied for one chamber at the time. Immediately after digestate application the chamber was placed on top and measurements started for that specific chamber. For machine applied digestate (trial 2) all digestate was applied within 5 min. Thereafter, all chambers were placed and measurements started for chamber 1 and continued in numeric order. The chambers were placed in a randomized block design with all four treatments represented in a block. All treatments within a block were measured before moving on to the next block. The chambers were placed so they covered two slurry bands.

2.2. Test 1: Assessment of distribution uniformity by trailing hose/shoe boom

A 9 m slurry boom was used to assess digestate distribution. The slurry boom was divided into three sections, each with an application

Table 2
Results of slurry boom distribution test. With 18 hoses all hoses (3 sections × 6 hoses) were included in the calculations of mean, standard deviation (std. dev.), minimum and maximum, and coefficient of variation (CV). With 6 hoses the two central hoses from each section (3 sections × 2 hoses, Fig. 1) were included in the calculations of mean, sd, min-max, and CV.

Test	Number of hoses included	Digestate application rate (t ha^{-1})[a]	Mean amount of digestate (L min^{-1})	Std. dev.	Min - max	CV (%)
A	18	40	217	18	184–247	8
A	6	40	213	7	200–220	3
B	18	40	203	17	164–229	9
B	6	40	199	7	192–207	3
C	18	20	109	22	87–150	20
C	6	20	95	6	87–101	6

[a] Digestate flow equivalent to application rate in the column, at a driving speed of 12 km h^{-1}.

technique (trailing hose or variety of trailing shoe) allowing for application with three application techniques simultaneously (Fig. 1). Each section had 6 outlets spaced 250 mm apart. The slurry tank was filled with digestate (dry matter = 2.99 %). Each hose outlet discharged into a 200 L barrel while the pump operated at a flow corresponding to an application rate of 40 t ha^{-1} (tests A and B) or 20 t ha^{-1} (test C) at 12 km h^{-1}. Mass gain in each bucket was measured using a scale and used to calculate flow through each hose. Three tests were conducted in total.

2.3. Test 2: Effect of driving speed on ammonia emissions

Two field trials (2a and 2b) examined ammonia emissions after digestate application by trailing hose (TH) and trailing shoe (TS) (TSB, Samson Agro A/S, Denmark) at driving speeds of 4 and 12 km h^{-1}. Each treatment applied 32 t ha^{-1} digestate. The digestates had very similar properties in the two trials (Table 1). Cumulative ammonia emission served as the response variable in a three-factor fully-crossed analysis of variance (ANOVA) (factors: speed, application method, trial), with Tukey's test for pairwise comparison. A single flux chamber was used as the unit of analysis and the cumulative ammonia emission was used as the response variable. For each treatment, 4 replicate measurements (chambers) were used.

2.4. Test 3: Effect of hose distance

To assess the impact of band spacing, two trials (3a and 3b) were conducted using both unseparated and centrifuge-separated digestate. The dry matter of the two fractions was 3.7 and 1.7 % for the unseparated and separated digestate in trial 3, respectively, and 3.5 and 3.0 % for the unseparated and separated digestate in trial 4, respectively. Spacings of 120, 250, and 300 mm were tested. Differences among treatment were analysed for each trial using a three-way factorial analysis of covariance (ANCOVA) with separation status, hose distance (numeric), and trial as the predictor variables. A single flux chamber was used as unit of analysis and cumulative ammonia emission was response variable. For each treatment, 3 replicate measurements (chambers) were used.

2.5. Test 4: Effect of flux chamber relocation

One single field trial (4) tested whether relocating dynamic flux chambers influenced measured emissions. Chambers were either fixed (1 position), alternated between two positions daily (2 positions), or moved to new plots daily (7 positions). Difference among treatments was analysed using one-way analysis of variance (ANOVA) with treatment (changing chamber position) as the independent variable. A single flux chamber was used as the unit of analysis and cumulative ammonia emission was the response variable, with Tukey's test for pairwise comparison. For each treatment, 5 replicate measurements (chambers) were used.

3. Results and discussion

3.1. Test 1: Assessment of distribution uniformity by trailing hose/shoe boom

Variation among hoses was considerable, with up to 42 % difference between minimum and maximum flow of slurry at the lowest application rate (test C) (Table 2). The coefficient of variation (CV) ranged from 8 to 20 %. When using the dynamic flux chambers in the field, they are placed on top of two slurry bands, therefore, an effort was made to reduce the variation between the total of 6 hoses (3 sections × 2 hoses, Fig. 1) that would be used for measurements of ammonia emission. By selecting six hoses with near-average flow and positioning two of them centrally in each boom section (section = one application technique), CV decreased to 3–6 % (Table 2), ensuring consistent application rates across the three spreading methods two central hoses. Proper hose selection and equalization of outlet flow were therefore crucial for achieving representative results in subsequent field trials.

3.2. Test 2: Effect on driving speed on ammonia emissions

Although average relative emission reduction with trailing shoe compared to trailing hose was greater at 4 km h^{-1} (42–62 %) than at 12 km h^{-1} (25–55 %) (Table 3) in both trials, statistical tests did not show main or interaction effects of driving speed ($p > 0.2$). The present results are not sufficient to draw general conclusions on the effect of driving

Table 3
Cumulative ammonia loss (% of total ammoniacal nitrogen (TAN) applied) (mean ± standard deviation, $n = 4$) after application digestate A with trailing hose or trailing shoe at two different driving speeds. Difference (%) is the relative difference between application by trailing hose and trailing shoe as a percentage of trailing hose emission.

		Emission (% applied TAN)		
Trial	Driving speed (km h^{-1})	Trailing hose	Trailing shoe	Difference (%)
2a	12	24.5 ± 4.6	11.1 ± 4.1	55
2a	4	26.0 ± 2.8	10.0 ± 2.9	62
2b	12	28.4 ± 9.9	21.2 ± 5.4	25
2b	4	24.2 ± 8.6	14.1 ± 2.1	42

Table 4
Cumulative ammonia loss (% of total ammoniacal nitrogen (TAN) applied) (mean ± standard deviation, $n = 3$) after application of untreated digestate and its liquid fraction after separation mimicking trailing hose application with different distance between the hoses.

		Distance between trailing hoses		
Trial	Digestate	300 (mm)	250 (mm)	120 (mm)
Emission (% applied TAN)				
3a	Unseparated	25.1 ± 2.7	25.8 ± 0.2	20.5 ± 2.1
3a	Liquid fraction (separated)	−4.9 ± 7.4	4.9 ± 4.1	
3b	Unseparated	34.7 ± 8.5	45.1 ± 2.6	33.8 ± 4.8
3b	Liquid fraction (separated)	7.6 ± 3.7	8.0 ± 0.7	

Table 5
Cumulative ammonia loss (% of total ammoniacal nitrogen (TAN) applied) (mean ± standard deviation, $n = 5$) after application of slurry digestate followed by keeping chambers in a fixed location or relocating them daily.

Trial	Treatment	Emission (% applied TAN)
4	1 position	30.9 ± 4.6
4	2 positions	32.4 ± 3.5
4	7 positions	38.5 ± 3.4

speed. However, they indicate that under certain conditions or combinations of conditions as well as application techniques driving speed may affect both the cumulative emission and relative differences between application methods. We hypothesize that the effect is due to enhanced placement quality and thereby reduced exposed surface area at lower driving speed.

3.3. Test 3: Effect of hose distance

Across both trials, no clear main effect of hose distance was detected ($p = 0.31$). A weak interaction ($p = 0.065$) between digestate separation and spacing appeared and was due to unusually low emissions from separated digestate in trial 3a (−4.9 ± 7.4 %). When those data were excluded, no significant differences remained ($p \geq 0.74$). Despite non-significance, on average, unseparated digestate in trial 3b emitted 23 % more ammonia at 250 mm than at 300 mm spacing (Table 4), implying that an effect of spacing on emissions under certain conditions cannot be excluded.

3.4. Test 4: Effect of flux chamber relocation

Chambers relocated daily to a new position (7 positions) exhibited 25 % higher cumulative emissions (38.5 ± 3.4 %) than stationary chambers (1 position) (30.9 ± 4.6 %) ($p = 0.023$) (Table 5). Alternating between two positions daily (2 positions) produced intermediate results (32.4 ± 3.5 %) (Table 5) without significant difference from the other two treatments ($p = 0.82$).

Dynamic flux chambers may overestimate ammonia emissions because greater turbulence inside the chamber compared to natural wind over the soil (Hafner et al., 2024). This likely explains the higher emissions observed when chambers were relocated to new positions. In the 7 positions treatment, fluxes were higher on days 2 and 3 (Fig. 2 and S1), suggesting that freshly uncovered areas retained more available TAN than plots previously measured for 24 h. The combination of higher emission in chambers compared to open plots and regular movement to a new location would introduce a positive bias in emission measurements. No precipitation occurred during the trial, but rainfall would likely have promoted digestate infiltration and reduced TAN availability outside the chamber area, probably altering this effect.

These findings confirm that chamber relocation introduces bias, supporting the decision to keep chambers stationary throughout measurement periods. The latter, however, may be connected to a different emission dynamics as in situations without chamber measurements, as the increase in emissions by relocation indicates a higher remaining emission potential at locations after days without chamber placement.

3.5. Recommendations

Based on the experiments presented in this work, we can recommend considerations that should go into planning and execution of field trials for measurement of ammonia emission from field-applied slurry or similar tasks based on measurements made in small field plots. In general, small plot application methods should be similar to realistic full-scale application unless it can be shown that differences are not important. Consistency in application rate among equipment hoses should not be assumed but verified and possibly adjusted. Lastly, moving dynamic chambers (including wind tunnels) during a measurement trials is not recommended.

CRediT authorship contribution statement

Johanna Pedersen: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Sasha D. Hafner:** Writing – review & editing, Formal analysis. **Andreas S. Pacholski:** Writing – review & editing.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used ChatGPT (GPT-

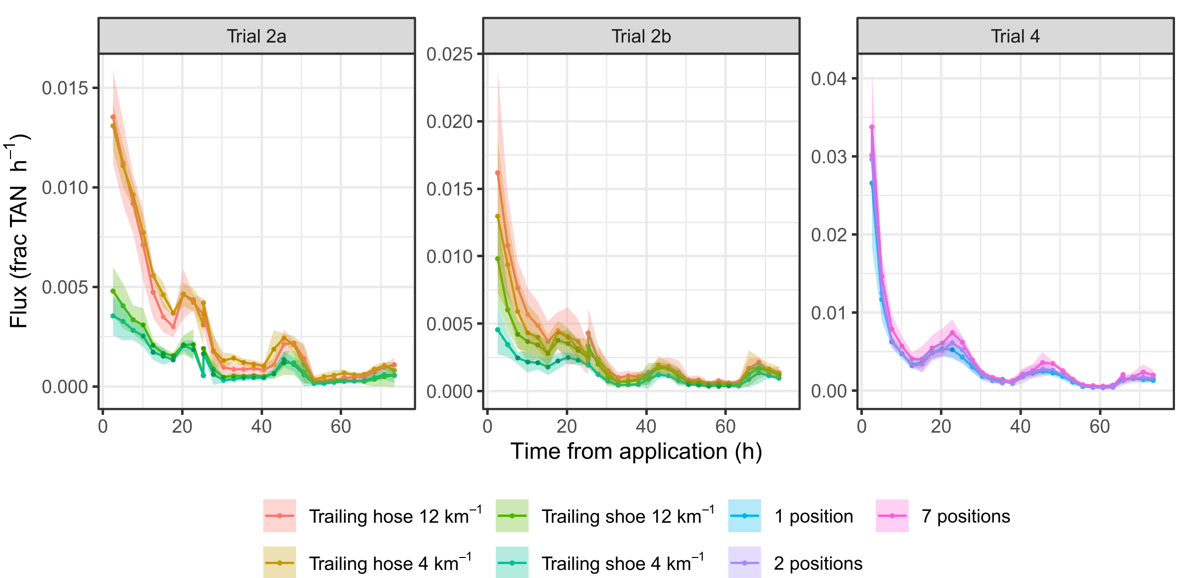

Fig. 2. Ammonia emission rate (as a fraction of applied total ammoniacal nitrogen (TAN) h^{-1}) after application of digestate by trailing hose or trailing shoe with a driving speed of 12 or 4 km h^{-1} (trials 2a and 2b) or after application of digestate by trailing hose and with a different strategy regarding chamber relocation (trial 4). Plot titles show trial ID. Standard deviations are displayed in bands ($n = 3$). Measurements were conducted for 160 h, but only the first 75 h after application is shown in the plot to make differences between treatments in the first period clearer.

5, OpenAI) to condense proportions of the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aeaoa.2025.100408.

Data availability

Most data and associated scripts are available at [Zenodo: 10.5281/zenodo.17903443].

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