MANAGEMENT EFFECTS ON METHANE EMISSION FROM STORED DIGESTATE
- INSIGHTS FROM COUPLING HEAT TRANSFER AND MICROBIAL MODELS

SASHA D. HAFNER, HENRIK B. MØLLER, FREDERIK R. DALBY & CRISTIANE ROMIO

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Management effects on methane emission from stored digestate

- Insights from coupling heat transfer and microbial models

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AUTHORS:

Sasha D. Hafner, Henrik B. Møller, Frederik R. Dalby, Cristiane Romio

Department of Biological and Chemical Engineering

Aarhus University

AARHUS UNIVERSITET
DCA - NATIONALT CENTER FOR FØDEVARER OG JORDBRUG

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Preface

The project aims to reduce the climate and environmental impact associated with the management of livestock manure in slurry storage. Aarhus University has characterized digested manure from selected Danish biogas plants and developed a model-based approach that can estimate digestate temperature and methane emissions from digestate storage. Model inputs include delivery temperature, digestate composition, tank dimensions, and weather. Measurements from four full-scale tanks were used for parameter estimation and evaluation.

The report has been prepared based on a contract with SEGES Innovation P/S and Aarhus University. The Danish Technological Institute and SEGES contributed measurement data used in this work, including methane emission and temperature.

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Abstract

The quantity of methane emitted from digestate stored after anaerobic digestion and effects of management are not well characterized. In this work two existing mechanistic models—a heat transfer model for digestate temperature and a microbial model for methane production—were coupled to provide a complete tool for predicting methane emission from stored digestate. Measurements from two full-scale storage tanks were used for parameter estimation. An evaluation of the models was done using measurements from two additional full-scale tanks. The models predicted overall levels of annual emission for the two tanks reserved for evaluation with relative error under 20%. Predicted dynamics in emission rate over a year were roughly similar to measurements, with some significant exceptions where the model predicted a very different annual pattern. Temperature was predicted relatively accurately (mean absolute error 3.2 °C or lower), reflecting the simplicity of the underlying processes, in contrast to methane emission. For both models, differences come from model error but also errors in input data and uncertainty in emission measurements. The coupled models can be used to explore potential effects of digestate properties, weather, tank conditions, delivery temperature, or other management practices, on methane emission. Predictions suggest that the quantity of degradable substrate remaining in digestate is an important variable, and that sensitivity to the delivery temperature depends on the digestate loading/emptying schedule, resulting from interactions between timing, heat transfer rates, substrate hydrolysis, and the relatively slow growth of methanogenic communities. Predictions do not include estimates of uncertainty, but uncertainty is undoubtedly high, and predicted effects will likely change as future measurements are used to refine model parameters and perhaps model structure.

1 Introduction

Anaerobic degradation of liquid animal manure (slurry) during storage results in methane (CH_4) production (Dalby et al., 2021a), which makes a significant global contribution to climate change (IPCC, 2022). Anaerobic digestion of slurry prior to on-farm storage could potentially reduce methane loss to the atmosphere by reducing the quantity of stored degradable organic material. Limited full-scale measurements suggest that this in fact may be true (Vechi et al., 2023). However, differences in management could have a substantial effect on emission. For example, the temperature of delivered digestate depends on heat recovery practices at the biogas plant. And the digestate addition/removal schedule determines the quantity of digestate present in a tank over an annual cycle. Both delivery temperature and digestate quantity interact to affect digestate temperature (Hafner and Mjöfors, 2023), which can have a large effect on CH_4 emission through changes in hydrolysis rate and microbial activity (Dalby et al., 2021a). Untangling these and other interactions to determine the effects of anaerobic digestion and management on CH_4 emission is not a trivial task, largely because of the complexity of the microbial processes leading to methane emission.

The aim of the present work was to develop a method and software tool for predicting the effect of management on methane emission from digestate storage after biogas production. Parameter estimation and model evaluation relied on full-scale measurements that will be described in a separate publication by Pernille Kasper et al. The remainder of this document describes how the work was carried out (Section 2) and summarizes results (Section 3).

2 Methods

In this work two mechanistic models were coupled to predict stored digestate temperature and methane emission. STM (for Storage Temperature Model) was used for digestate temperature (Hafner and Mjöfors, 2023), and ABM (for Anaerobic Biodegradation Model) for methane production (Dalby et al., 2023). A subset of model parameters were estimated and the models were evaluated using emission measurements from four full-scale digestate storage tanks. Model inputs for these tanks were based on tank dimensions, digestate level measurements, digestate delivery records, analysis of digestate samples taken from the tanks, and weather data.

2.1 Emission and related measurements

Four digestate storage tanks with tent-type covers were included in this work (Table 1). Each tank received digestate from a separate full-scale biogas reactor. The primary substrate for all was animal manure, at about 75% of the fresh mass. The organic fraction of municipal solid waste made up the largest part of the remainder for AD1, AD2, and AD4. For AD3, this balance consisted of other waste products and crops. Calculated hydraulic retention time was 44 days for AD1 and AD2, and 31 days for AD3 and AD4.

Table 1. *Characteristics of the four digestate storage tanks studied in this work. All were located in Jutland, Denmark.*

Tank ID	Capacity (m^3)	Annual digestate load (t)	Annual volatile solids (VS) load (t)	Annual CH_4 emission (t)	Annual CH_4 emission (kg/t digestate)	Annual CH_4 emission (kg/t VS)
AD1	5000	4100	230	7.4	1.8	33
AD2	2500	2200	110	5.9	2.6	53
AD3	1350	1600	76	2.5	1.6	33
AD4	1800	2200	100	3.5	1.6	34

Methane emission was measured from each tank using a tracer method on multiple dates over at least 6 months. Emission measurements on tanks AD1 and AD2 started in July or August 2022 and ended around early May 2023. For tanks AD3 and AD4, measurements started in July or early September 2023 and ended in March 2024. Emission measurements were used for parameter estimation and model evaluation in this work. Some details on the emission measurement system (for AD1 and AD2) were presented in a Danish language report (Kasper and Holm, 2022). Additional details were presented at a conference in 2024 (Kasper and Holm, 2024). And a paper presenting methods and results for all tanks is expected in 2025 with Pernille Kasper (Danish Technological Institute, Aarhus Denmark) as the first author. For the present work, Pernille Kasper shared emission measurements as multiple emission rates (between 20 and 200) measured over sampling periods of 1 to 12 days for the four tanks. These measurements were used for parameter estimation and model evaluation as described below in section 2.3.

Digestate samples were collected from post-digestion storage tanks at the biogas plants (i.e., prior to on-farm storage in AD1 etc.) on two or three occasions and analyzed for residual methane potential (RMP) starting on the day of collection, and for chemical parameters after storage at 4 °C at the AU Viborg biogas laboratory (Table 2). Residual methane potential (RMP, mL CH_4 / g digestate VS) was measured by incubating digestate samples anaerobically at 51 °C without any added inoculum. Biogas volume was measured volumetrically using an acidified water column, and methane concentration was determined by gas chromatography as described by Romio et al. (2023).

For use of ABM, RMP was converted to a concentration of total degradable substrate in chemical oxygen demand units (COD) (g COD / kg digestate) using the COD equivalence of methane (350 mL CH_4 / g COD). In ABM, particulate degradable substrate (VS_d in the model documentation, in COD units) is hydrolyzed and fermented to volatile fatty acids (VFA, also in COD units, actually representing all reduced fermentation end products, including multiple VFAs and H_2), which then serve as substrate for methane production. Input VS_d was therefore calculated as total degradable substrate (from RMP) minus the measured VFA concentration. See Table 2 for values used in the reference simulations.

Table 2. *Average measured digestate characteristics (for most, n = 3 digestate samples taken from the biogas plants) including derived variables used as ABM inputs. RMP = residual methane potential, VFA = volatile fatty acids. VS degrad. = apparent degradability of measured VS based on RMP, an assumed COD:VS ratio of 1.449 (from supplementary material in Dalby et al., 2021b, as in default ABM settings), and measured VS concentration. Note that this degradability is the fraction of total VS degraded during the RMP test, and this fraction is not typically completely converted to CH_4 during digestate storage. VS and TAN (total ammoniacal nitrogen) are expressed per kg of digestate fresh mass.*

	VS	RMP	Degradable substrate (g COD / kg digestate)					TAN
Tank	(g/kg)	(ml CH_4 / g VS)	Particulate*	VFA	Total*	pH	VS degradability* (%)	(g/kg)
AD1	55.3	88	13.9	0.34	14.24	8.29†	17	2.4
AD2	50.0	64	9.2	2.48	11.64	8.02	13	2.9
AD3	48.5	122	16.9	0.22	17.12	7.91	24	2.6
AD4	47.4	109	14.7	0.26	14.97	8.00	22	2.6

Notes: *Derived variables calculated from VS, RMP, and VFA measurements. Total degradable substrate is the sum of particulate substrate (VS_d in ABM) and VFA concentrations. †This measured value resulted in implausibly high ammonia inhibition for a functioning digester based on the default inhibition parameters in ABM, so pH was fixed at 8.00 for ABM simulations.

2.2. Application of the heat transfer model STM

The STM model v1.1 (Hafner and Mjöfors, 2023) was used to simulate daily digestate temperature dynamics. Model inputs include tank dimensions (inner diameter and maximum depth), daily weather, and a digestate level table, which reflects loading and removal. The digestate level table was developed for each tank by combining: 1) sparse tank level measurements made manually in conjunction with some of the emission measurements and 2) complete digestate delivery records. Digestate removal events were inferred based on mismatches between the cumulative sum of loading and the measured digestate level; where the sum of loaded digestate exceeded the measured level, a removal event must have occurred prior. However, the exact timing of digestate removal was unknown, so an attempt was made to follow typical patterns (Fig. 1). Precipitation and evaporation were neglected, which is reasonable because the tanks were all covered. Digestate delivery records for AD3 included some volume actually delivered to an adjacent tank not included in this study, and so the delivery quantity to AD3 was reduced by two-thirds in proportion to tank volumes. Resulting slurry quantity is shown in Fig. 1 for all four tanks.

STM uses daily measurements of air temperature and global solar radiation (W/m^2), which were taken from spatially gridded weather data from the Danish Meteorological Institute (DMI). STM includes a default parameter set (currently v1.0) with heat transfer resistance and related terms for uncovered concrete tanks (https://github.com/AU-BCE-EE/STM-applications, Hafner and Mjöfors (2023)). The tent covers installed on the four tanks studied in this work are expected to increase resistance to heat transfer between the digestate surface and the atmosphere and increase capture of solar radiation. Therefore, the values of two parameters were adjusted to better fit measured temperature for tanks AD1 and AD3: the resistance term for air was increased 15-fold from 0.02 to 0.3 K m^2/W and absorptivity was increased from 0.019 to 0.03 (dimensionless). The direction of both changes was based on expected effects of a tent, and magnitudes were based on an improvement in reproducing average measured tank temperature, i.e., fitting to measurements. The effect of a cover on heat transfer is complex and difficult to estimate without detailed air flow measurements. But even a small layer of completely or nearly still air could account for the 15-fold increase in resistance employed here, so the changes are plausible. And by reducing surface heat loss, a cover would be expected to increase the absorptivity term, which represents the net fraction of solar radiation energy incident on the tank transported into the slurry, as described in the original STM paper (Hafner and Mjöfors, 2023)

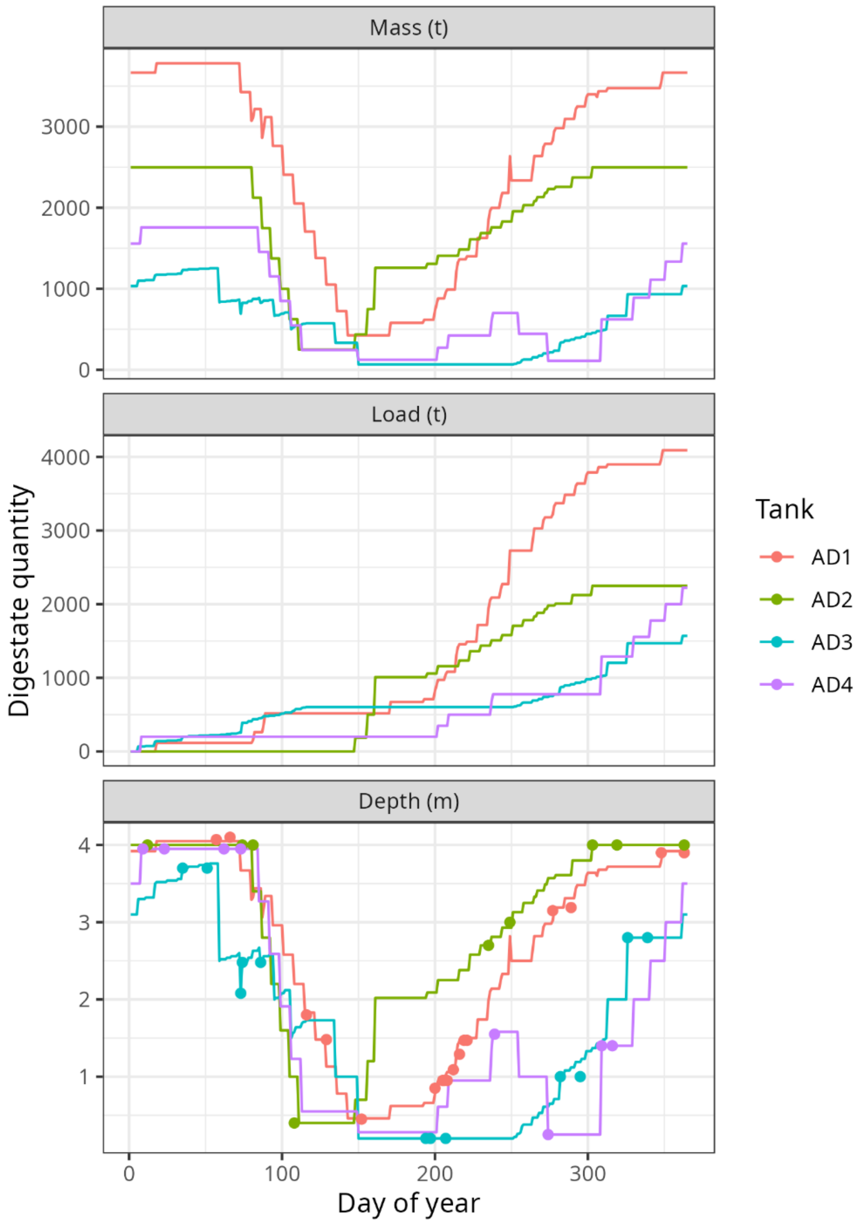

Figure 1. *Inferred digestate quantity (mass in tank, cumulative annual load delivered to tank, and digestate depth in tank) for the four storage tanks used in the model simulations. The points in the slurry depth plot (bottom) are based on measured slurry surface height.*

2.3. Application of the methane production model ABM

STM returns daily digestate temperature. These data were combined with digestate properties (Table 2) to use as input to the microbial model ABM, which was then used to predict methane emission. ABM is described in detail in Dalby et al. (2021b) and is available online (https://github.com/AU-BCE-EE/ABM).

In the present work, ABM parameter values were adjusted from v2.0 default values developed by fitting to measurements earlier, with changes to the hydrolysis rate (arrh_pars in ABM) to better capture measured emission rates from AD1 and AD3, which showed very different emission patterns. (Values for parameters related to hydrolysis and microbial growth are given in the appendix in Table A1.) The microbial parameters (grp_pars in ABM) were also adjusted, to have two methanogen groups with temperature optima at 36 and 42 °C to ensure plausible responses of the microbial community to temperatures above 30 °C. The lack of these groups in the default set is related to a paucity of emission measurements under these conditions. Predictions from ABM were compared to the mean values of emission measurements for each sampling period as well as cumulative annual emission. Measurements from AD2 and AD4 were reserved for model evaluation.

Calculation of annual emission from the 5-6 mean emission measurements available from each tank required numerical integration. Trapezoidal or other integration methods based on measured emission rate (kg/d) appeared to overestimate total emission by estimating a high rate during periods of low slurry mass. The integration process was carried out in four steps to reduce this problem. First, emission rate in kg/d was divided by inferred slurry depth (estimated from level measurements and digestate delivery information as described in section 3.1), resulting in a normalized emission rate in kg/d-m. This new variable was then interpolated at a daily resolution. This step is based on the assumptions that the best estimate of volumetric or mass-based emission rate is between the nearest available measurements, and that volumetric emission rate is always closer in magnitude to the measurement closer in time.

Daily interpolated emission rate was then calculated as the product of depth-normalized emission rate and slurry depth, and annual total was estimated as the sum of daily estimates,

$$E = 1\,\mathrm{d} \sum_{d=1}^{365} n_{i,d} z_d, \qquad (1)$$

where E = estimated total annual emission (kg CH_4), $n_{i,d}$ = interpolated depth-normalized emission rate for day d (kg d^{-1} m^{-1}), z_d = inferred digestate depth on day d (m), and the constant $1\,\mathrm{d}$ converts rates to daily emission.

A total of 20 different simulation scenarios were evaluated for each of the four storage tanks. The reference scenario "a" was meant to represent the best estimate of reality. Other scenarios were developed to quantify sensitivity of predictions to changes in inputs and parameter values (Table 3).

Table 3. *Simulation scenarios, which differed in parameter values or input variable values. Scenario "a" represents the best estimate of reality. Digestate temperatures given in the table are delivery (loading) temperatures, not the temperature of digestate in the storage tank.*

Key	Scenario description
a	Reference
b	Low digestate level (1 m or maximum possible subtracted)
c	High digestate level (1 m or maximum possible added)
d	Measured temperature (interpolated)
e	Low digestate loading (level changes divided by 2 or maximum possible)
f	High digestate loading (level changes multiplied by 2 or maximum possible)
q	Low hydrolysis (rate divided by 5)
g	High hydrolysis (rate multiplied by 5)
i	10°C digestate
h	15°C digestate
o	20°C digestate
l	25°C digestate
m	35°C digestate
n	40°C digestate
j	45°C digestate
k	45°C digestate and high hydrolysis (hydrolysis rate multiplied by 5)
p	Low methanogen growth rate (rates divided by 5)
r	High methanogen growth rate (rates multiplied by 5)
s	High degradable substrate concentration (28 g/kg VS_d, 0 g/kg VFA)
t	Low degradable substrate concentration (8 g/kg VS_d, 0 g/kg VFA)

3 Results and discussion

3.1 Tank temperature

Predicted temperature was quite close to measurements for AD1, and less so for the other tanks. But still, error was not large; mean absolute error was 3.2 °C for AD4, where high loading toward the end of the measurement period caused a large increase in the temperature predicted by STM. It seems likely that some uncertainty in loading rate, timing, or delivery temperature contributed to differences, but model error could still be the main contributor to the difference. Error was lower for the other tanks. Digestate temperature does not closely follow air temperature; in general, digestate temperature was higher, and changes show a delay or lag compared to air temperature (Fig. 2). Loading complicates trends as well. For example, around day 300 (end of October) measured temperatures range from 23 °C (AD1) to around 10 °C (AD4). AD1, AD2, and AD3 all show steep drops in measured temperature during a period of increasing air temperature late in the year. STM was generally able to predict both of these observations. So, while prediction of stored digestate temperature is not trivial and cannot be based on air temperature alone, STM, which is a simple mechanistic model with low input requirements, may be sufficient. STM is simple to set up for use and quick to run; each simulation presented here required less than 0.02 seconds to run on a desktop computer with a 3.20 GHz Intel Core i5-3470 processor.

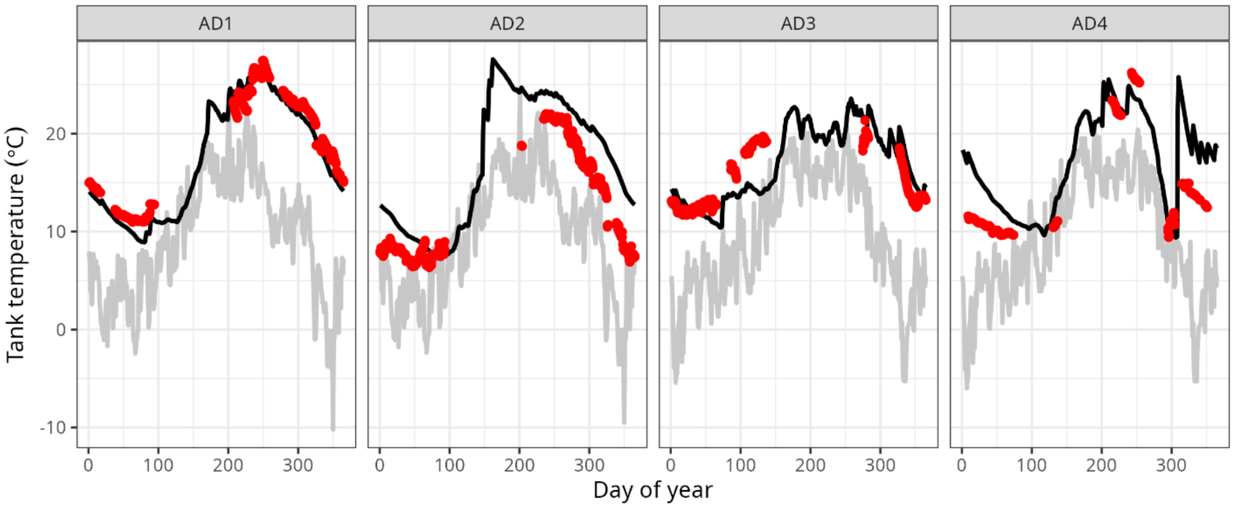

Figure 2. *Comparison between average measured temperature of digestate within the four storage tanks (red points) and values calculated by STM as described in Section 2.1. Light gray lines show air temperature. All values are daily averages.*

3.2 Methane emission

It is more challenging to replicate methane emission patterns, and more difficult to evaluate model predictions given less frequent measurements (measurement of emission rate is much more complex and difficult than measurement of digestate temperature). But ABM generally reproduced measured emission rates for AD1 and AD3, which were used for parameter adjustment and therefore do not provide a true evaluation of the model (Fig. 3) (model efficiency for emission rate (kg/d) was 0.58 for AD1 and 0.84 for AD3). AD2 and AD4 are more appropriate for ABM evaluation. Model performance for AD2 was perhaps acceptable (model efficiency of 0.44, mean bias error of -6.5 kg/d), but performance was poor for AD4 (model efficiency of -0.07, mean bias error of 1.6 kg/d). For AD4, ABM predicted low CH_4 emission in the summer and higher winter emission because of a generally low digestate level in the summer. Emission measurements showed the inverse (Fig. 3). The difference reflects model error but error in inputs undoubtedly contribute as well. The peak measured emission rate, which was much higher than the model prediction, was also higher than any other measurements, especially when normalized by the mass of digestate present (78 g/d-t, while the next closest values were 21 and 15 g/d-t). Error in estimated digestate mass likely contributed to the discrepancy. In ABM it is not only digestate mass at the time of emission measurement that affects emission; the timing of digestate loading has an effect also, because it affects the availability of methanogen substrates produced through hydrolysis and fermentation, as well as development of the microbial community.

When expressed as total annual emissions, ABM predictions for the reference scenarios were close to measurements (Fig. 4). For the reference scenarios, the model calculated annual emissions of 8.0, 4.8, 2.2, and 3.3 t CH_4 for AD1, AD2, AD3, and AD4, respectively. Not surprisingly, error was small for AD1 and AD3 (8% and -11%), but relative error was only -19% for AD2 and -7% for AD4. Evaluation of ABM based on annual emission (in contrast to emission rate) somewhat reduces the importance of hydrolysis rate and changes in the microbial community, and so is less challenging. Both measured and predicted emission varied widely among the four tanks when normalized by VS loading, reflecting differences in apparent organic matter degradability (based on laboratory RMP tests) and the timing of loading. The annual measured value was about 56% higher for AD2 (53 kg CH_4 / t VS) than AD4 (34 kg CH_4 / t VS). This was true despite apparent degradability of AD4 VS actually being higher (Table 2) (although this difference is tempered by a higher VFA concentration in AD2 digestate). The difference in normalized emission is likely related to the loading schedules. AD2 received a large fraction of total digestate load between day of the year 150 (beginning of June) and 250 (early October) when the temperature in the tank was high. AD4 received very little digestate in this period, and the level in the tank was low (Figs. 1 and 5). ABM only partially captures this difference, with the VS-normalized emission value 36% higher for AD2 than AD4.

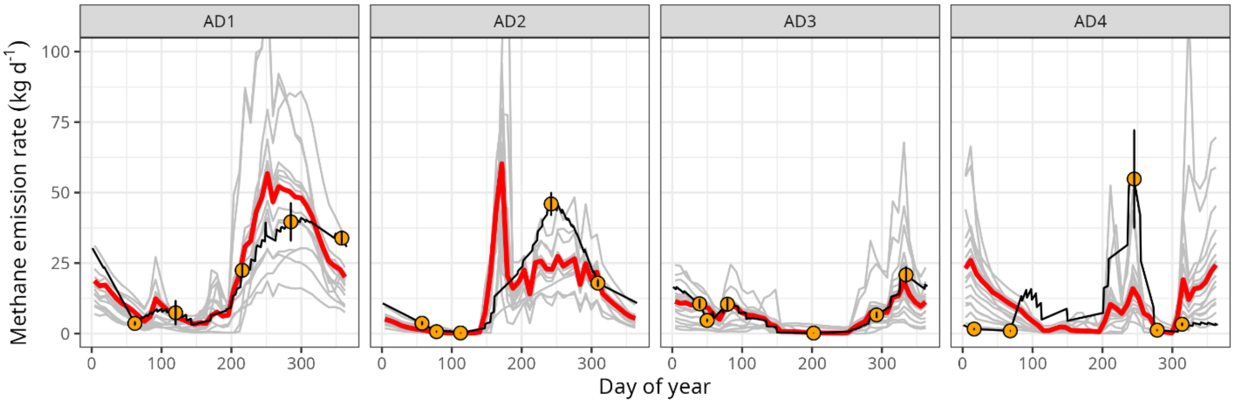

Figure 3. *Comparison of measured and model-calculated methane emission from the four digestate storage tanks. The red lines show ABM predictions for the reference scenario ("a"), with digestate temperature predicted by STM. Light gray lines show results from all other scenarios. All ABM predictions are averaged in 8 d bins to better match the averaging of measurements. Orange circles show measured emission rates, with error bars based on approximate 90% confidence intervals. Black lines show interpolated measured emission, reflecting changes in slurry quantity (section 2.3).*

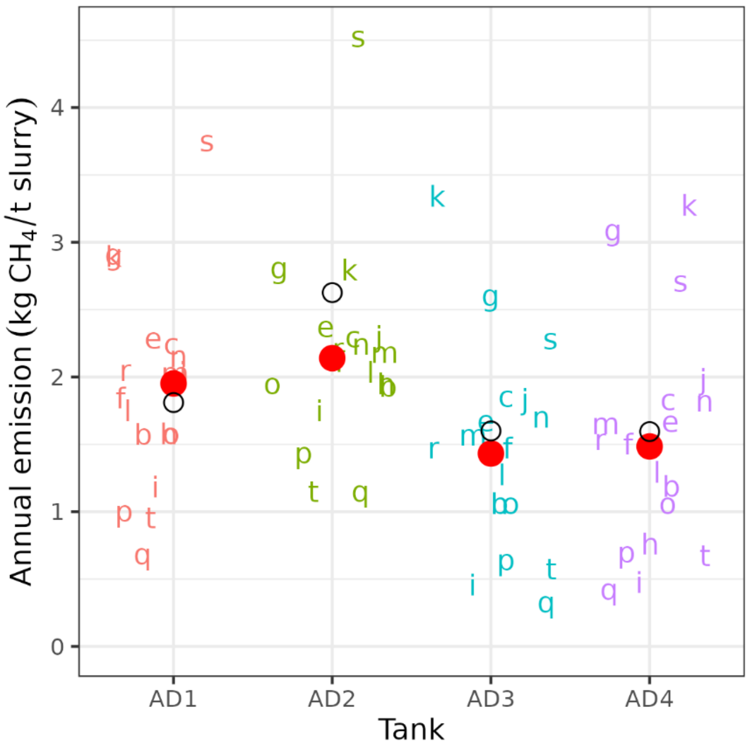

Figure 4. *Total annual emission, measured (black circles) and calculated with ABM (red circles show reference scenario "a" results) normalized by slurry loading. Letters correspond to scenarios in Table 3.*

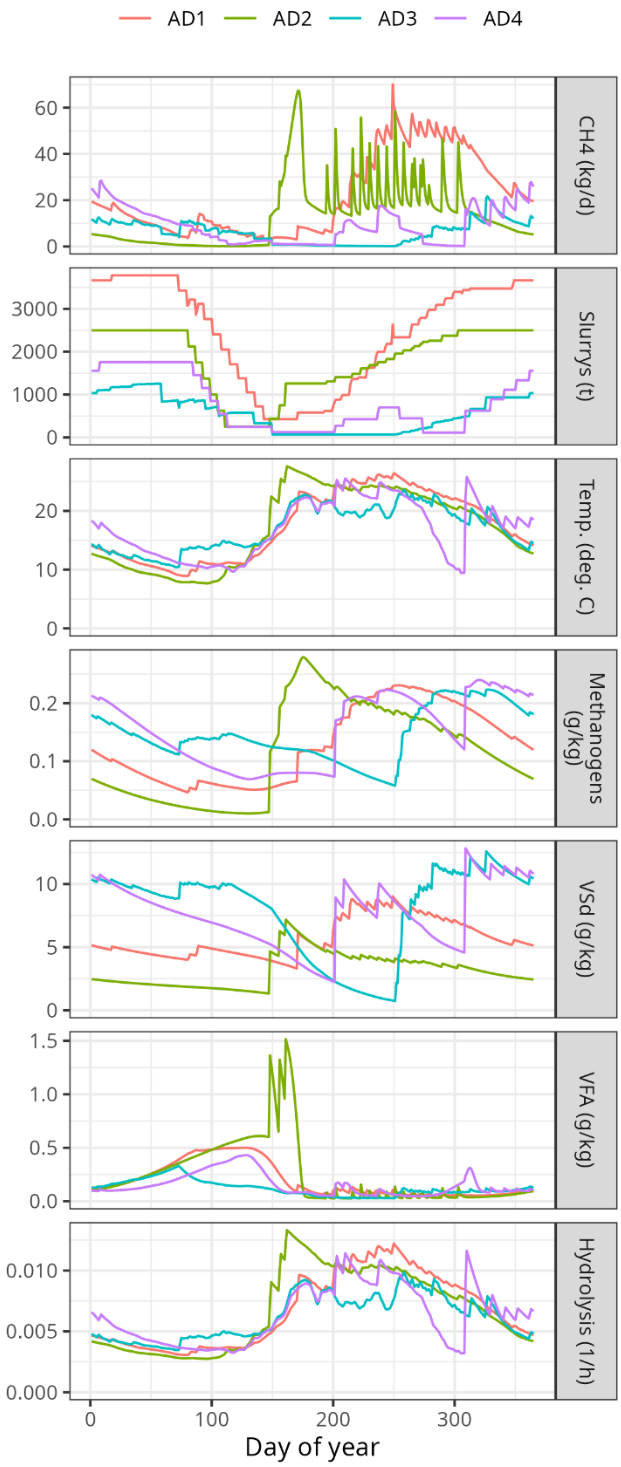

Figure 5. *Temperature calculated from STM and several important variables calculated by ABM for the reference scenario "a" for all four tanks. Results are daily values.*

Predicted emission for the reference scenario (Fig. 4) was within the wide range of values measured from full-scale digestate storage tanks. Making this comparison required a conversion, because literature values are typically presented as average emission rates per m^3 of digestate present. The loading-based values presented above are more consistent with the current understanding of the processes controlling emission, and can inform inventory estimates, but annual loading is not typically measured, limiting the units that can be presented in other studies. To compare, daily predicted emission rate was divided by daily digestate volume, and averages of this normalized value were calculated. Resulting averages ranged from 8.6 (AD2) to 12 g/d-m^3 (AD4). Vechi et al. (2023) measured average rates from 7 to 26 g/d-m^3 for uncovered tanks and 6 to 65 g/d-m^3 from tent covered digestate slurry tanks in Denmark. Balde et al. (2016) measured an annual average of 19 g/d-m^3 from manure-based digestate on a Canadian dairy farm. Values calculated by ABM in the present work therefore do not seem unusual.

3.3 Predicted sensitivity

Variation in parameter values and input variables included in the sensitivity simulations (Table 3) showed that many are likely to affect emission. In particular, the quantity of degradable substrate was important, with an approximate doubling leading to a nearly proportional increase in annual emissions, although the relative effect varied among tanks, highlighting the importance of interactions between substrate delivery and other variables (compare scenarios s and t to the reference scenario in Fig. 4). Considering parameter values, hydrolysis rate was important (compare scenarios q and g to the reference in Fig. 4). Given high variability in measured or estimated rates of hydrolysis (Dalby et al., 2021b), hydrolysis rate is clearly one important source of uncertainty in model predictions.

A subset of scenarios (Table 3) was used to explore predicted sensitivity of the coupled models to the temperature of delivered digestate. Resulting STM predictions show substantial sensitivity, and also highlight effects of the loading schedule, most obviously the lack of temperature sensitivity with little or no loading (e.g., AD3 around day 200) (Fig. 6). ABM predictions (Fig. 7) show a positive sensitivity for all tanks, but, interestingly, large differences in the magnitude of the response. The loading schedule is important for explaining these differences. For example, AD2 has low temperature sensitivity because much of the digestate was delivered during summer and early fall when tank temperature was high. Conversion of substrate to CH_4 was largely limited by substrate supply (loading) for AD2, according to ABM. In contrast, AD4 had a high sensitivity to delivery temperature because more loading occurred during cool periods when increased hydrolysis and methanogenic activity can substantially increase conversion of substrate.

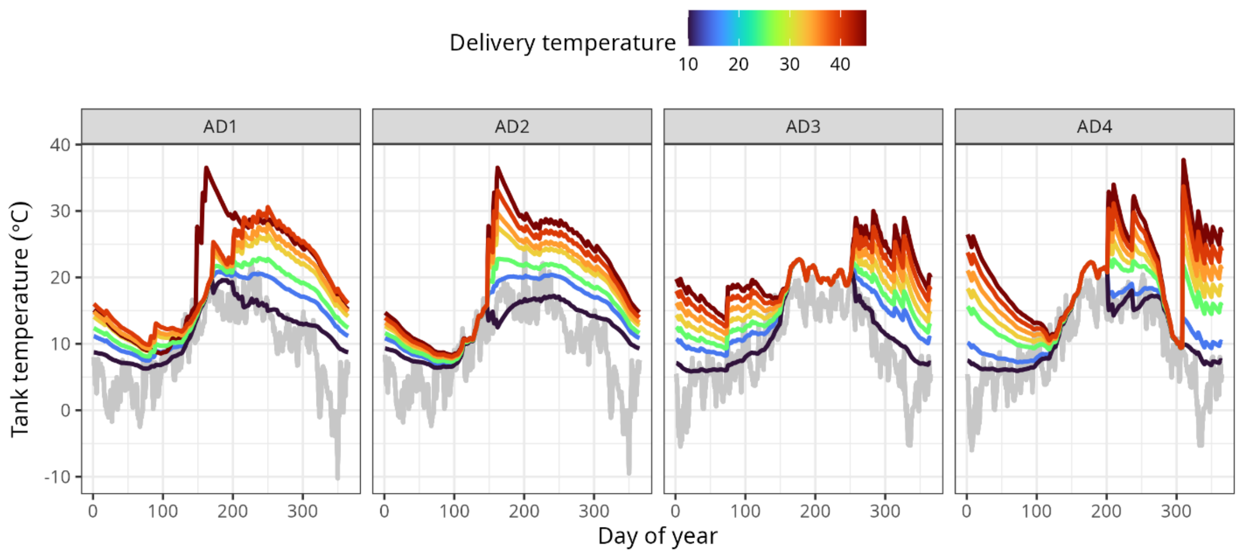

Figure 6. *Predicted temperature of digestate within storage tanks in response to differences in the temperature of delivered digestate, from 10 to 45 °C. Gray line shows air temperature, all others show STM predictions of digestate temperature within each storage tank.*

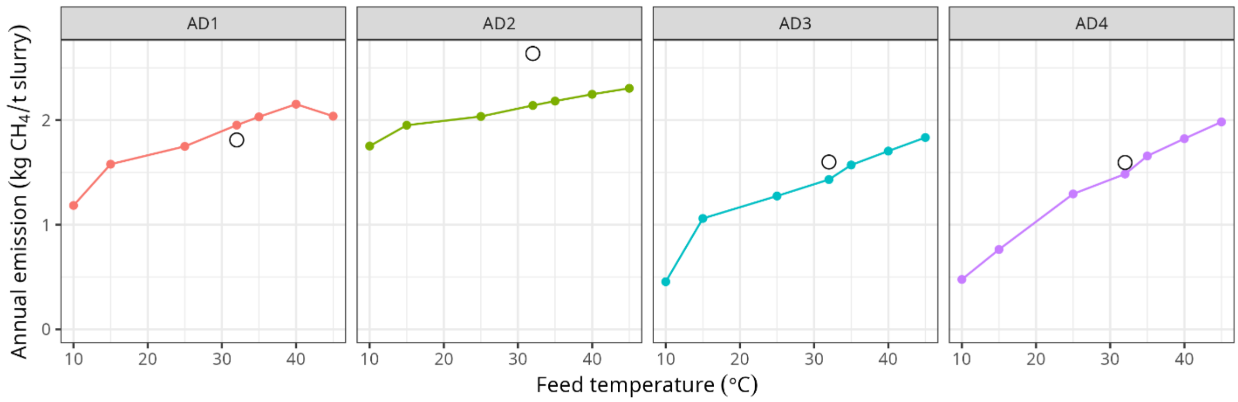

Figure 7. *Annual methane emission predicted by ABM based on STM predictions of temperature in response to differences in the temperature of delivered digestate, from 10 to 45 °C. Black circles show measured values bases on numerical integration as described in section 3.3.*

4 Conclusions

Coupled mechanistic models for stored digestate temperature and methane emission were able to reproduce and partially predict observed patterns over time and among tanks, and therefore provide a tool for exploring potential effects of digestate properties, weather, tank conditions, delivery temperature, or other management practices on emission. Predictions suggest that the quantity of degradable substrate remaining in digestate affects methane emission substantially. The coupled models show that management changes that affect temperature, such as digestate delivery temperature, can have large effects as well. However, sensitivity to delivery temperature will vary among tanks due to interactions with loading. Uncertainty in predictions is undoubtedly significant and there is a need for additional model evaluation and parameter estimation at digestate temperatures above 30 °C (primarily for ABM) and for tanks with tent-type covers (for STM).

References

Baldé, H., VanderZaag, A.C., Burtt, S.D., Wagner-Riddle, C., Crolla, A., Desjardins, R.L., MacDonald, D.J., 2016. Methane emissions from digestate at an agricultural biogas plant. Bioresource Technology 216, 914–922. https://doi.org/10.1016/j.biortech.2016.06.031

Dalby, F.R., Hafner, S.D., Petersen, S.O., VanderZaag, A.C., Habtewold, J., Dunfield, K., Chantigny, M., Sommer, S.G., 2021a. Understanding methane emission from stored animal manure: A review to guide model development. Journal of Environmental Quality. https://doi.org/10.1002/jeq2.20252

Dalby, F.R., Hafner, S.D., Petersen, S.O., Vanderzaag, A., Habtewold, J., Dunfield, K., Chantigny, M.H., Sommer, S.G., 2021b. A mechanistic model of methane emission from animal slurry with a focus on microbial groups. PLOS ONE 16, e0252881. https://doi.org/10.1371/journal.pone.0252881

Hafner, S.D., Mjöfors, K., 2023. STM: A software tool for predicting daily temperature in stored animal slurry. SoftwareX 22, 101354. https://doi.org/10.1016/j.softx.2023.101354

IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926

Kasper, P., Holm, M. 2022. Ammoniakemission fra teltoverdækkede gyllebeholdere. SEGES Innovation, Aarhus N, Denmark.

Kasper, P., Holm, M. 2024. Emissions of ammonia and methane from farm-scale tent-covered manure storages. Presented at the EmiLi 2024 Conference in Valencia, Spain.

Romio, C., Kofoed, M. V. W., Møller, H. B., 2023. Exploring increased hydraulic retention time as a cost-efficient way of valorizing residual biogas potential. Bioresour. Technol. 387, 129646. https://doi.org/10.1016/j.biortech.2023.129646

Vechi, N.T., Falk, J.M., Fredenslund, A.M., Edjabou, M.E., Scheutz, C., 2023. Methane emission rates averaged over a year from ten farm-scale manure storage tanks. Science of The Total Environment 904, 166610. https://doi.org/10.1016/j.scitotenv.2023.166610

Appendix

Table A1. *Values used in this work for ABM parameters. Not all parameters are given but all that differ from default values are included (scale_alpha_opt, qhat_opt, T_opt, T_min, and T_max), along with some others related to microbial activity.*

ABM parameter	Group[1]	Value	Units	Details
yield	m*	0.05	g COD/g COD	Fixed yield for all methanogens
yield	sr1	0.065	g COD/g COD	For sulfate reducer group
xa_fresh		0.0628	g COD/kg digestate	Live microbial biomass concentration in feed
xa_init		0.0628	g COD/kg digestate	Initial microbial biomass concentration in tank
decay_rate		0.02	1/d	Microbial biomass decay rate
ks_coefficient	m*	1.153	g COD/kg digestate	Half velocity coefficient for Monod model
ks_coefficient	sr1	0.461	g COD/kg digestate	Half velocity coefficient for Monod model
scale_alpha_opt		2.7	-	Multiplier for maximum hydrolysis rate
qhat_opt	m1	1	g COD/(kg digestate)-d	Maximum metabolic rate for Monod model
qhat_opt	m2	2	g COD/(kg digestate)-d	Maximum metabolic rate for Monod model
qhat_opt	m3	3	g COD/(kg digestate)-d	Maximum metabolic rate for Monod model
qhat_opt	m4	5	g COD/(kg digestate)-d	Maximum metabolic rate for Monod model
qhat_opt	m5	7	g COD/(kg digestate)-d	Maximum metabolic rate for Monod model
qhat_opt	sr1	9	g COD/(kg digestate)-d	Maximum metabolic rate for Monod model
T_opt	m1	18	°C	Optimum temperature
T_opt	m2	18	°C	Optimum temperature
T_opt	m3	28	°C	Optimum temperature
T_opt	m4	36	°C	Optimum temperature
T_opt	m5	42	°C	Optimum temperature
T_opt	sr1	44	°C	Optimum temperature
T_min	m1	0	°C	Minimum temperature
T_min	m2	6	°C	Minimum temperature
T_min	m3	6	°C	Minimum temperature
T_min	m4	15	°C	Minimum temperature
T_min	m5	30	°C	Minimum temperature
T_min	sr1	0	°C	Minimum temperature
T_max	m1	25	°C	Maximum temperature
T_max	m2	25	°C	Maximum temperature
T_max	m3	38	°C	Maximum temperature
T_max	m4	45	°C	Maximum temperature
T_max	m5	55	°C	Maximum temperature
T_max	sr1	51	°C	Maximum temperature

Notes: 1. Microbial group: m* = all five methanogen groups, m1 = first methanogen group etc., sr1 = only sulfate reducer groups, blank = all microbes (methanogens and sulfate reducer group).

Table A2. *Values used in this work for STM parameters. All other parameters in the parameter file (Hafner and Mjöfors, 2023, section 2.1.2) were kept at v1.0 values.*

STM parameter	Value	Units	Notes
R_air	0.3	K-m^2/W	Air-side heat transfer resistance from top of digestate, includes effect of cover
absorptivity	0.03	-	Effective absorptivity of top surface of digestate, or the fraction of incoming solar radiation absorbed by the digestate

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SUMMARY

Methane emission from digestate stored after anaerobic digestion and effects of management are not well characterized. In this work a heat transfer model for digestate temperature and a microbial model for methane production were coupled to provide a tool for predicting methane emission from stored digestate. Measurements from full-scale storage tanks were used for parameter estimation and evaluation. The models predicted overall levels of annual emission with relative error under 20%. Predicted dynamics in emission rate over a year were roughly similar to measurements, with some exceptions where the model predicted a different annual pattern. Temperature was predicted accurately (mean absolute error < 3.2 °C). The coupled models can be used to explore potential effects of digestate properties, weather, tank conditions, delivery temperature, or other management practices on methane emission. The quantity of degradable substrate remaining in digestate is an important variable, and sensitivity to the delivery temperature depends on the digestate loading/emptying schedule, resulting from interactions between timing, heat transfer rates, substrate hydrolysis, and slow growth of methanogenic communities. Predictions do not include estimates of uncertainty, but uncertainty is undoubtedly high, and predictions will likely change as the models are refined.