Model development and validation for estimating methane and ammonia emissions from fattening pig houses: effect of manure management system

P. Sefeedpari[1,*], S.H. Pishgar-Komleh[1] and A.J.A. Aarnink[1]
[1]*Wageningen Livestock Research, P.O. Box 135, 6700 AC Wageningen, The Netherlands*
[*]Corresponding author: Paria Sefeedpari, paria.sefeedpari@wur.nl

Abstract

This paper describes a calculation model for the prediction of methane and ammonia emissions from fattening pig houses. This model was validated with continuous and discrete measurements from two manure management systems (MMS) (long storage (LS) in deep pits and short storage (SS) by daily flushing of a shallow pit with sloped walls). The average calculated methane and ammonia emissions corresponded well with the measured values. Based on the calculated and measured results, the average calculated CH_4 emission (18.5 and 4.3 kg pig^{-1} yr^{-1}) corresponded well with the continuous measured values using sensors (15.9 and 5.6 kg pig^{-1} yr^{-1}) and the discrete measurements using the reference method (22.0 and 3.1 kg pig^{-1} yr^{-1}) for LS and SS, respectively. The average calculated NH_3 emission (2.6 and 1.4 kg pig^{-1} yr^{-1}) corresponded well with the continuous measured values using sensors (2.6 and 1.2 kg pig^{-1} yr^{-1}) and the discrete measurements using the reference method (2.7 kg pig^{-1} yr^{-1} and 1.0) for LS ad SS, respectively. Based on the results of the reference measurements, the approximate reduction potential of these measures for CH_4 and NH_3 emissions is 86% and 63%, respectively. The upgraded model with robust calculation rules, extensive validations and a simplified interface can be a useful tool to assess the current situation and the impact of mitigation measures at the farm level.

Keywords: methane emission, ammonia emission, modelling, manure, pig house

Introduction

Intensive pig production contributes strikingly to global methane (CH_4) and ammonia (NH_3) emissions, which are among the most important contributors to climate change (Le Dinh et al, 2022; Zong et al, 2015). By intensification of pig farming systems and therefore indoor storage of liquid manure, better estimation of methane and ammonia emissions as affected by manure management system (MMS) will help to tackle environmental burdens effectively (De Vries et al, 2013). In recent years, various measures have been applied to reduce GHG emission from pig houses resulting in several low-emission housing systems (O'Mara, 2011). Frequent (daily) removal of manure by flushing the pit underneath the slatted floor has been shown to be an effective means to reduce methane and nitrogen emissions (Amon et al, 2007; Feng et al, 2022; Groenestein et al, 2011; Philippe and Nicks, 2015; Vechi et al, 2022). These measures can be applied in various variants and levels at farm-level.

Measuring the effects of all these variants is both time and cost consuming. One cost-effective alternative to measurements is to use models by which the effect of various measures can be assessed at farm level. The objective of this study was to develop and validate a calculation model to assess and predict the effect of housing and manure management on methane and ammonia emissions from fattening pig houses. The outcome of this study provides a good basis for calculating the effects of management and housing measures on methane and ammonia emissions from pig houses, thereby contributing to attaining more sustainable pig farming practices.

Materials and methods

General description of calculation model (ANIPRO)

The model approach has a mechanistic approach as much as possible, however a number of relationships have been established empirically. In addition, for a few parameters calibrations were performed on measurement data, i.e. the value of a parameter (e.g. a regression coefficient) has been estimated based on the best fit on the measured data. These features provide possibilities to determine the effect of mitigation measures on methane and ammonia emissions by representing the effect of design of the housing system, nutrition and other management aspects in a pig farm. Model simulations were done at daily time resolution throughout a growing period (GP).

The calculation model starts with the calculation of the daily feed and water intake throughout the entire production period. The dynamics of growth curves and the total consumption of feed and drinking water of pigs are described with a Gompertz function (Aarnink et al, 2018). Based on the production stage of the pig, the uptake of metabolizable energy, the (calculated) growth curve, and nutrients (nitrogen) retention are calculated. With the digestion coefficients of the feed and the calculated retention rates, the amount and composition of faeces and urine can be estimated. Since there is also a water balance, the concentrations can also be calculated over a growing period. Physical characteristics as well as the indoor climate conditions of the pig houses have been incorporated in this model. The ammonia emission per m^2 emitting surface can be calculated for different emitting surfaces, including emissive floor and emissive manure pit surface. By multiplying these source strengths (emission per m^2) by the size of the emitting surfaces, the total ammonia emission and the ammonia emission of each source can be determined individually (Aarnink et al., 2018). Within the methane model, the methane production rate per kg volatile solids of manure is estimated. By multiplying this rate by the total manure production, the total methane emission can be estimated.

The input variables of the model were: length of production period, initial and final weight of pigs, growth rate, total feed and water intake, feed composition, weather data (temperature and relative humidity), climate set-up, building specifications, storage time and water use. The outputs, among others, were animal performance, manure composition, and methane and ammonia emissions. Model calculations can be used for various pig categories, housing systems and manure pit designs. A detailed description of the calculation model as well as the algorithms for estimating methane and ammonia emissions can be found in Aarnink et al. (1992); Aarnink et al. (2018). In this study, a description of the principal rules and the additions to the existing model are addressed.

Validation of the model

In order to validate the model, experiments were conducted on two fattening pig pens. Continuous measurements (using sensors) included measurements of ammonia and methane concentrations, ventilation rates, temperature. Discrete measurements included manure production, manure composition, pen fouling (with urine), manure temperature and height in manure pit. Measurements for determining the concentration of methane and ammonia gases have been conducted using a reference method at specific times (two randomly selected days per growing period) over one year (October 2020 - 2021) (Booijen et al, 2022).

The first experimental pen represented a conventional manure management system with long-term storage of manure in deep pit underneath the slatted floor (LS) and the second experimental pen was equipped with an adapted slurry pit for short-term storage of manure by daily flushing from the pit underneath the slatted floor (SS). These two systems were examined for the mitigation potential of methane and ammonia emissions affected by the manure removal frequency, pen design and dilution with water. The characteristics of the farms and a schematic representation of the housing systems are presented in Table 1 and Figure 1.

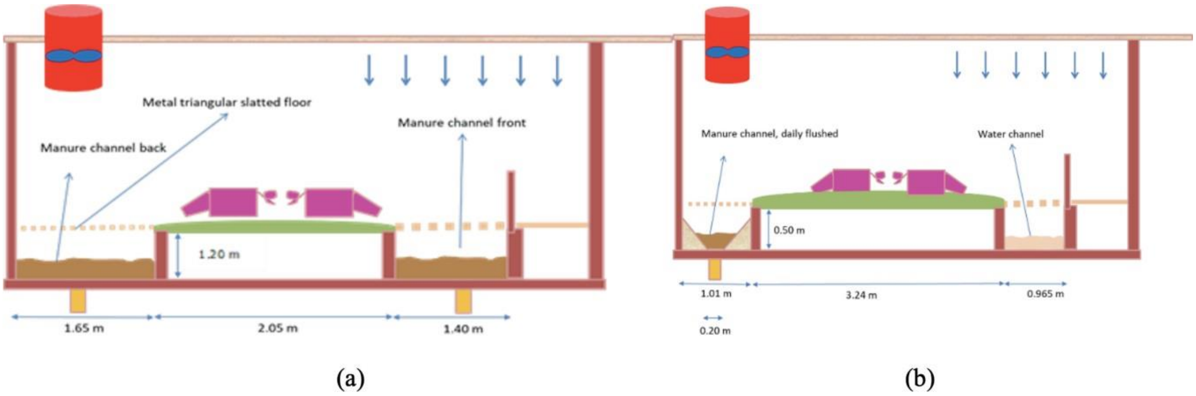

Figure 1: Schematic representation of the fattening pig farms a) long-term storage and b) short-term storage of manure inside the pig house.

Table 1 Overview of the experimental pig farm with two manure management systems.

Characteristics	LS [1]	SS [2]
No. of animals	54	78
Average body weight (kg)	23.6 – 115.6	22.6 - 114
Room length (m) × width (m)	11.28 × 5.90	15.55 × 6.00
No. of pens	6	6
Pen length (m) × width (m)	5.10 × 1.88	5.22 × 2.59
Depth of manure pit	1.20	0.50
Area per animal (m^2 pig^{-1})	1.00	1.00
Material slatted floor (back-front slatted floor)	Metal triangular - Concrete	Metal triangular - Concrete
Material solid floor	Concrete	Concrete
Slatted floor / Solid floor (%)	60	38
Slope manure pit wall (°)	90	45
Manure removal interval (d)	45 [3]	1
Feeding / drinking system	Dry feeder / Nipple	Dry feeder / Nipple

[1] LS: long term storage of manure; [2] SS: Short term storage; [3] Mean of emptying interval

Results and discussion

Modelling of methane emission and validation

A summary of the calculated and measured room temperature, manure temperature, volatile solids and methane emission for the LS and SS storage structures are presented in Table 2. All emissions data represents the mean daily values converted to annual emissions. Based on the obtained results, the average values of most of the measured parameters were comparable with the calculated values for the two MMS. The average room temperature was about 23 °C in LS and 21 °C in SS. The average temperature of manure was measured as 24.5 °C and 22.3 °C, respectively. The lower temperature ranges in SS can be explained by the short storage courses and daily removal of manure in this system. In general, manure temperature was underestimated by the model ($P < 0.01$). The manure temperature was calculated by using empirical relationships with the room temperature measured. This significant difference in manure temperature suggests the need to consider temperature variation by the depth at inside storages in countries such as the Netherlands where long-term manure storage inside the pig houses is a common practice. The calculated VS content of manure was slightly lower than the measured value (ca. 10%). This is perhaps due to the underestimation of the water evaporation rate from the manure. Furthermore, an underestimation of the relative humidity has been also detected with an insignificant difference from the measured values (Table 2).

Table 2: Average calculated and measured room temperature, manure temperature, volatile solids and methane emission per system for fattening pigs. Standard deviations are given between parentheses.

Variable	MMS	Calculated	Measured - Continuous	Measured - in-vivo [1]	P [2]	RMSE [3]
Room temperature (°C)	LS	22.3 (1.6)	23.0 (1.8)	-	0.006	4.0
	SS	21.4 (2.7)	21.0 (2.6)	-	0.45	3.8
Manure temperature (°C)	LS	19.5 (1.3)	-	24.5 (1.7)	0.01	6.5
	SS	18.7 (2.2)	-	22.3 (2.4)	< 0.001	7.5
Volatile solids-manure (g kg^{-1})	LS	68.5 (5.9)	-	76.2 (11.5)	0.02	12.5
	SS	68.0 (7.3)	-	77.4 (9.0)	0.09	31.8
CH_4 emission (kg pig^{-1} yr^{-1})	LS	18.5 (5.3)	15.9 (7.9)	22.0 (5.0)	0.3	12.7
	SS	4.3 (2.4)	5.6 (3.7)	3.1 (1.3)	< 0.001	4.0

[1] Reference method (Booijen et al., 2022); [2] p-value: probability that continuous measured and calculated values are equal to each other; [3] root mean square error between calculated and continuous measured vales based on daily differences.

Figure 2 depicts the calculated methane emission in two MMS and the height of manure in the pit representing manure volume. From this figure, prediction of volume of the stored manure and the corresponding methane emission fitted well with the measurements. The breaks seen in this graph are due to partly emptying of the pit in this farm. No continuous measurement data were available for the first growing period (GP1) due to unreliable sensor calibrations. Based on the results of the in-vivo measurements (the reference method) for the SS, a reduction potential of 86.0% (± 5.6%) can be expected. The results show that daily removal of manure can largely reduce methane emissions. Monteny et al. (2001) reported that approx. 1.5 kg pig^{-1} $year^{-1}$ of methane is produced by pigs. Thus, it is to be expected that with SS most methane emission from manure could be prevented.

Another general observation was that beside the manure management, the emission of each fattening period was influenced by the seasonal effect in both measurements and modelling results as well as in both LS and SS systems (Figure 2). The highest methane emission occurred in summer during periods (GP3 and GP4) with maximum outside temperatures (June-July). Feng et al. (2022) have recently shown that methane emission was highly dependent on frequency of manure removal and less dependent on temperature of the manure in storage with increased manure removal frequencies in pig houses. Therefore, more research into the impact of indoor temperature on methane emissions from slurry pits inside the Dutch pig houses is required.

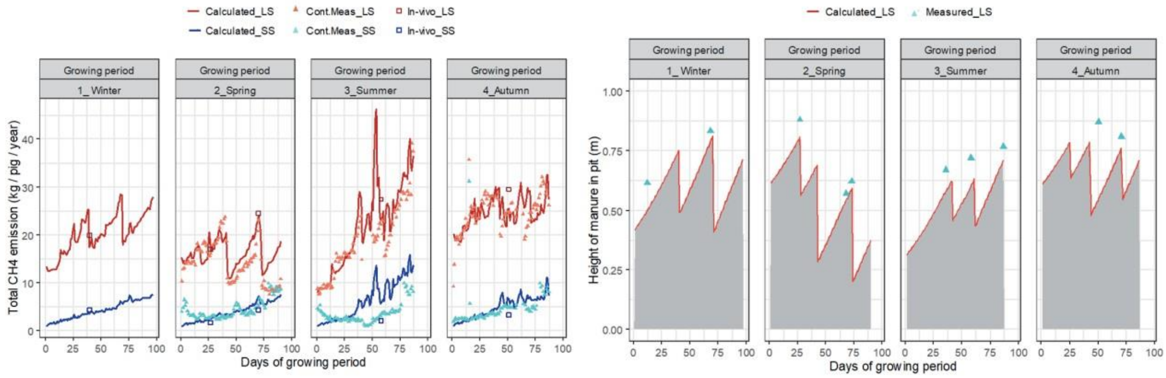

Figure 2: Calculated (line) and measured (point) methane emission (kg pig^{-1} yr^{-1}) per growing period (GP) for two manure management system: LS: long storage in pit with straight walls (blue line and points) and SS: short storage in pit with sloped walls (red line and points). All data represents the mean daily values converted to annual emissions. The 'Cont. Meas' category indicates the continuous measurements using sensors. The 'in-vivo' data indicates the discrete reference measurements. In growing period 1 no sensor measurements were recorded. The start and end date of the growing periods were: GP1: 8/10/20 - 12/1/21; GP2: 21/1 - 20/4/21; GP3: 27/4 - 21/7/21; GP4: 27/7- 21/10/21.

The linear relationships between the continuous-measured and calculated methane emission are shown in Figure 3. The results show better agreements between the continuous measurements and predicted values in the LS than the SS. This can be improved by better estimation of the manure temperature and the manure fraction deposited in the front (water) channel. This channel was discharged once per growing period.

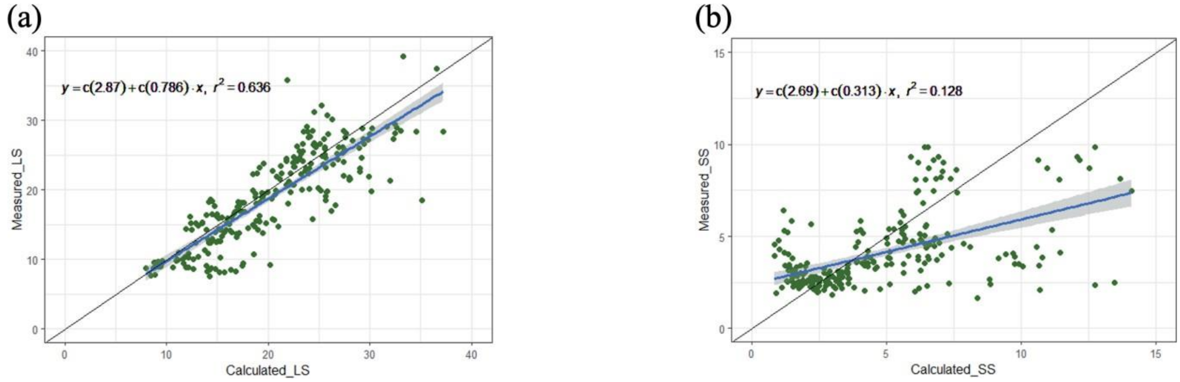

Figure 3: The continuous measured (Y) and calculated (X) methane emission (kg pig^{-1} yr^{-1}) in a) LS: long storage in pit with straight walls; b) SS: short storage in pit with sloped walls. The solid black line represents the 1:1 line. All data represents the mean daily values converted to annual emissions.

Modelling of ammonia emission and validation

A summary of the calculated and measured ammonia emission per source (manure pit and soiled floor surface) during one year are presented in Table 3. The average values of most of the measured parameters were comparable with the calculated values. Mean calculated ammonia emission in LS and SS were 2.64 (± 1.05) and 1.39 (± 0.75) kg pig^{-1} yr^{-1}, respectively. No significant difference was found between the calculated and measured parameters, confirming the accuracy of the model predictions. Comparing the emissions produced from the floor and manure pit, it can be concluded that manure pit contributes to 80% of the NH_3 emissions inside the pig houses. This result highlights the impact of mitigation measures on reducing NH_3 emission from manure storage pits compared to the floor. In pig houses, the proportion of the solid floor as regards NH_3 emissions is a limiting factor. Many studies has shown that lower ammonia emissions can be achieved with partly slatted floor provided that the solid part of the floor remains clean (Koerkamp et al, 1998; Philippe et al, 2011; Sun et al, 2008). The risk of soiling is greater by a larger proportion of solid floor. A good pen design and maintaining a good climate in the house (e.g. lower begin temperature of the ventilation and use of floor cooling in the summer) can ensure a lower risk of NH_3 formation from the solid floor (Aarnink et al., 2018).

Table 3: Average calculated and measured ammonia emission (floor, manure pit and the total amount) per system for fattening pigs. Standard deviations are given between parentheses.

Variable	MMS	Calculated	Measured - Continuous	Measured - in-vivo [1]	P [2]	RMSE [3]
NH_3 emission - Floor	LS	0.46 (0.28)	-	-	-	-
(kg pig^{-1} yr^{-1})	SS	0.46 (0.27)	-	-	-	-
NH_3 emission - Manure	LS	2.17 (0.91)	-	-	-	-
pit (kg pig^{-1} yr^{-1})	SS	0.93 (0.56)	-	-	-	-
Total NH_3 emission	LS	2.64 (1.05)	2.57 (0.88)	2.71 (0.38)	0.4	1.2
(kg pig^{-1} yr^{-1})	SS	1.39 (0.75)	1.19 (0.92)	1.01 (0.23)	0.5	0.8

[1] Reference method (Booijen et al., 2022); [2] p-value: probability that continuous measured and calculated values are equal to each other. [3] root mean square error between calculated and continuous measured vales based on daily differences.

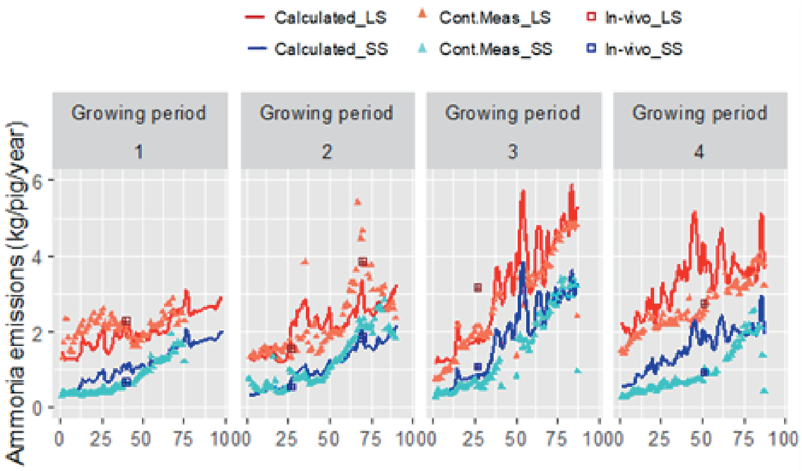

Figure 4: Calculated (line) and measured (point) ammonia emission (kg pig^{-1} yr^{-1}) for two manure management system: LS: long storage in pit with straight walls (blue line and points); SS: short storage in pit with sloped walls (red line and points). Category 'Cont.Meas' indicates the continuous measurements using sensors. Category 'in-vivo' indicates the discrete reference measurements. Breaks are due to problems with the sensor or outlier detection. The start and end date of the growing periods were: GP1: 8/10/20 - 12/1/21; GP2: 21/1 - 20/4/21; GP3: 27/4 - 21/7/21; GP4: 27/7- 21/10/21.

The measured and calculated ammonia emission per pig is presented in Figure 4. This figure shows that the development of ammonia emission was reasonably well predicted. The reduction of the slurry pit surface with sloped pit walls, frequent manure removal and dilution with water has shown promising reductions in ammonia emission of the SS. To be expected is that the average reduction of the SS is around 62.7% based on measurements by the reference method (in-vivo method).

The linear relationships between the daily measured and calculated ammonia emission per MMS are shown in Figure 5. The slope of the linear regression line was 0.63 with R^2 of 0.46 for the LS. For the SS, higher slope and R^2 were observed. Model predictions can be improved by better prediction of pH of manure. The current model is insufficiently suitable to predict the pH of manure. This is partly due to the fact that a large number of factors are affecting the pH, especially, the carbonate content of urine and manure is hard to predict. As an intermediate solution, the pH of urine and manure was measured and used as input to the model.

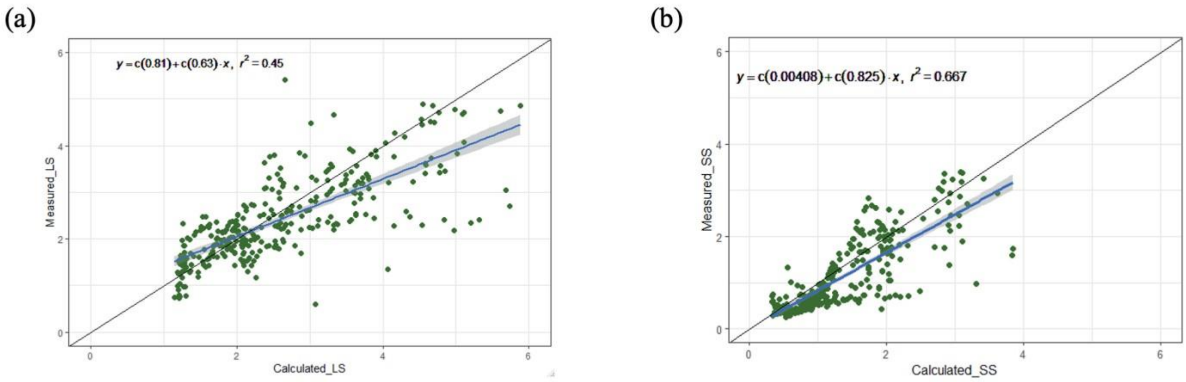

Figure 5: The measured (Y) and calculated (X) ammonia emission (kg pig^{-1} yr^{-1}) of two MMS a) LS: long storage in pit with straight walls; b) SS: short storage in pit with sloped walls. The solid black line represents the 1:1 line. Data represented the average daily values converted to annual emissions.

Model parameters and implications for the estimation of emissions

A model approach in estimating the influence of mitigation measures has been introduced in this study. The most critical component in these predictions is water excretion, due to the error caused by the incorrect estimation of water evaporation from manure and fouled floors with urine which is affected by the wind speed at surface. This parameter is assumed to be constant in the model.

Another challenge is estimating the pH of manure. The pH of the top layer of the manure was determined from the pH of the bulk of manure based on a lab-scale analysis at the University of Southern Denmark in Odense (Aarnink et al., 2018). Further development of the model should focus on accurate estimation of the pH by using a measurement set-up to measure the surface pH of the top 0.1 mm of manure comparable to practical situation or using the measured pH of the bulk manure as input into the emission model.

Another important point for improvement of the model is the assumption about the emitting surface. In this current version of the model, the ammonia emission per m^2 of contaminated concrete slatted floor was assumed to be the same as the concrete solid floor. This current model could be further improved by developing a dynamic urinary discharge model for the variation in ammonia emission over time as suggested by Aarnink and Elzing (1998).

Temperature and air velocity above the emitting surface were estimated from the measured temperature and ventilation quantity at exhaust which, although currently being easily measured, can be nevertheless improved by air flow models to better estimate the temperature and air velocity above different emitting surfaces. Extra effort is required to incorporate and apply these features into this model in a simple way. Further development of the methane emission model should be focused on temperature variation by the depth at inside storages and degradability of the organic matter over time for better estimation of methane emission.

Conclusions

The main conclusions from the research were:

- The current calculation model is sufficiently robust to assess the effects of housing, and management measures for methane and ammonia emissions from pig houses.
- The average calculated methane and ammonia emissions on an annual basis correspond well with measured values for the examined measures.
- The measurements confirmed the reduction potential of the studied measures for CH_4 and NH_3 emissions from pig houses. The model could predict these effects with an acceptable degree of accuracy.
- The calculation model can be further used to determine the effects of housing and management measures for methane and ammonia emissions.

Acknowledgment

This study was supported by the project grant of FACCE ERA-GAS under M4Models (Manure management for methane mitigation - Improved inventory modelling to support policy actions) project funded by the NWO and the Ministry of Agriculture, Nature and Food Quality in the Netherlands.

References

Aarnink A., Elzing A. (1998) Dynamic model for ammonia volatilization in housing with partially slatted floors, for fattening pigs. *Livestock Production Science* 53: 153-169

Aarnink A., Van Ouwerkerk E., Verstegen M. (1992) A mathematical model for estimating the amount and composition of slurry from fattening pigs. *Livestock Production Science* 31: 133-147

Aarnink, A., van de Pas, L., van der Peet-Schwering, C., Hol, A., Binnendijk, G., Le Dinh, P., Hafner, S. and Ogink, N. (2018) Rekentool voor het bepalen van de effecten van voer- en management-maatregelen op de ammoniakemissie bij varkens: ontwikkeling en validatie [Calculation tool to estimate the effects of feeding and management measures on ammonia emission in pigs]. *Wageningen Livestock Research* Wageningen, p. 118.

Amon B., Kryvoruchko V., Fröhlich M., Amon T., Pöllinger A., Mösenbacher I., Hausleitner A. (2007) Ammonia and greenhouse gas emissions from a straw flow system for fattening pigs: Housing and manure storage. *Livestock Science* 112: 199-207

Booijen M., Wagensveld J., van Riel J., de Mol R., van Bussel A., Aarnink A.J.A. (2022) Emissiereductie methaan, ammoniak en geur in varkensstallen met dagontmesting [Emission reduction of methane, ammonia and odor in pig houses with daily manure removal]. Wageningen Livestock Research. In press, p. 100.

De Vries J.W., Aarnink A.J.A., Groot Koerkamp P.W., De Boer IJ. (2013) Life cycle assessment of segregating fattening pig urine and feces compared to conventional liquid manure management. *Environmental Science and Technology* 47: 1589-1597

Feng L., Guldberg LB., Hansen MJ., Ma C., Ohrt RV., Møller HB. (2022) Impact of slurry removal frequency on CH4 emission and subsequent biogas production; a one-year case study. *Waste Management* 149: 199-206

Groenestein C., Smits M., Huijsmans J., Oenema O. (2011) Measures to reduce ammonia emissions from livestock manures: now, soon and later. Wageningen UR Livestock Research.

Koerkamp PG., Metz J., Uenk G., Phillips V., Holden M., Sneath R., Short J., White R., Hartung J., Seedorf J. (1998) Concentrations and emissions of ammonia in livestock buildings in Northern Europe. *Journal of Agricultural Engineering Research* 70: 79-95

Le Dinh P., van der Peet-Schwering CM., Ogink NW., Aarnink AJ. (2022) Effect of Diet Composition on Excreta Composition and Ammonia Emissions from Growing-Finishing Pigs. *Animals* 12: 229

Monteny G., Groenestein C., Hilhorst M. (2001) Interactions and coupling between emissions of methane and nitrous oxide from animal husbandry. *Nutrient Cycling in Agroecosystems* 60: 123-132

O'Mara FP. (2011) The significance of livestock as a contributor to global greenhouse gas emissions today and in the near future. *Animal Feed Science and Technology* 166: 7-15

Philippe F-X., Cabaraux J-F., Nicks B. (2011) Ammonia emissions from pig houses: Influencing factors and mitigation techniques. *Agriculture, Ecosystems and Environment* 141: 245-260

Philippe F-X., Nicks B. (2015) Review on greenhouse gas emissions from pig houses: Production of carbon dioxide, methane and nitrous oxide by animals and manure. *Agriculture, Ecosystems and Environment* 199: 10-25

Sun G., Guo H., Peterson J., Predicala B., Laguë C. (2008) Diurnal odor, ammonia, hydrogen sulfide, and carbon dioxide emission profiles of confined swine grower/finisher rooms. *Journal of the Air and Waste Management Association* 58: 1434-1448

Vechi NT., Jensen NS., Scheutz C. (2022) Methane emissions from five Danish pig farms: Mitigation strategies and inventory estimated emissions. *Journal of Environmental Management* 317: 115319

Zong C., Li H., Zhang G. (2015) Ammonia and greenhouse gas emissions from fattening pig house with two types of partial pit ventilation systems. *Agriculture, Ecosystems and Environment* 208: 94-105