

Calculation approaches for gaseous and odour emissions and the impact of a urease inhibitor in fattening pig houses

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Previous studies have shown that ammonia emissions can be continuously reduced through the application of a urease inhibitor (UI) in cattle and pig farming. However, there is no information on whether the use of these inhibitors also has an effect on other emissions, and whether it leads to an increase or decrease in these emissions.

In this study, carbon dioxide, ammonia, methane, nitrous oxide and odour emissions were measured in three mechanically ventilated, fully slatted pig fattening houses in Germany during 2019–2020. The UI was applied daily to compartments, and effects on emission values were comparatively analysed using four different calculation approaches: linear mixed model, direct case-control, case-control in time and a novel ratio-difference approach.

As expected, a significant reduction in ammonia emissions of 22–24% was observed across all four calculation approaches and all three farms, confirming the effectiveness of the UI; no decisive effects on carbon dioxide, methane or odour emissions were found. Effects on nitrous oxide emissions could not be reliably analysed due to low concentrations which were below the Fourier-transform infrared spectroscopy (FTIR) quantification limit.

It is recommended to calculate the reduction effect using a combined approach so that over- and underestimation of the effect can be avoided. Two approaches are available for this purpose: the ratio-difference and linear mixed model. The ratio-difference approach has a simplicity of calculation and the ability to achieve results very similar to those of the linear mixed model.

Keywords

Urease inhibitor, gaseous emissions, odour emissions, pig fattening, calculation approaches

Emissions released into the atmosphere are a risk to human health and the environment (ATSDR 2004, Erisman et al. 2008). There are a number of national and international political efforts to regulate and reduce emissions in the long term, such as the TA-Luft, National Emission Ceilings and the European Green Deal (EC 2016, 2021, BUNDESMINISTERIUM FÜR UMWELT, NATURSCHUTZ UND NUKLEARE SICHERHEIT 2021). Emissions can be categorised according to their relevance for climate change. Greenhouse gases such as carbon dioxide, methane and nitrous oxide contribute significantly to climate change, whereas ammonia and odour are not directly relevant to the climate, although ammonia will also have an indirect effect on nitrous oxide (PHILIPPE et al. 2007, GAVRILOVA et al. 2019).

In Germany, more than 92% of ammonia emissions and almost 8% of greenhouse gas emissions in carbon dioxide (CO₂) equivalents from carbon dioxide, methane and nitrous oxide come from agricultural

production. Of these, 49% of greenhouse gas and 70% of ammonia emissions come from livestock farming. Emissions in livestock farming are released and influenced in different ways (UBA 2025b, 2025a).

Carbon dioxide emissions are primarily caused by animal respiration and the manure in the slurry pit. The release of carbon dioxide is influenced by many factors, including respiratory quotient, animal heat production, body weight, production level and feed energy (NOBLET et al. 1989, PEDERSEN and SÄLLVIK 2002, PEDERSEN et al. 2008). In pig farming, methane originates from enteric fermentation by bacteria in the digestive tract and the anaerobic degradation of organic matter in manure. Methane production from enteric fermentation is mainly influenced by the crude fibre content in feed and the fermentative capacity in the gut. In manure, methane is produced under anaerobic conditions and is enhanced by higher temperatures (SOMMER and MØLLER 2000, PETERSEN and SOMMER 2011). Nitrous oxide is a by-product of the nitrification and denitrification processes which normally convert ammonia into inert dinitrogen gas. Nitrification requires aerobic conditions and denitrification requires anaerobic conditions. While only anaerobic processes occur in slurry, littered housing offers aerobic conditions. However, nitrous oxide emissions from manure on the floor can occur in pig houses with slatted floors and under-floor storage (PHILIPPE et al. 2007, GAVRILOVA et al. 2019). Odour emissions from pig houses are a very complex process that is influenced by many factors, such as the construction of the building, ventilation system, feed composition and manure management. In addition, odour emissions depend on the activity of the animals, and can differ greatly from subjective perceptions (ROMAIN et al. 2013, RZEŹNIK and MIELCAREK-BOCHEŃSKA 2022). The release of ammonia depends on many factors, such as pH value in urine and in slurry, temperature and the availability of ammoniacal nitrogen (KECK 1997). Ammonia is formed by the enzyme urease during the hydrolysis of urea. Urease is ubiquitously present on the floors of animal houses and is produced by microorganisms in faeces (VAREL 1997).

The use of a urease inhibitor is an approach directly linked to the enzyme urease. By reducing urease activity, the inhibitor prevents the hydrolysis of urea into ammonia (VAREL 1997, VAREL et al. 1999, LEINKER 2007). Various urease inhibitors were tested under laboratory conditions (in vitro) or practically in animal houses (in situ) in order to reduce emissions in animal farming. Notable among these are the urease inhibitor variants N-(n-butyl) thiophosphoric triamide (NBTP) (VAREL 1997, VAREL et al. 1999, TODD and MING 2001), cyclohexylphosphoric triamide (CHPT) (VAREL 1997, TODD and MING 2001) and inhibitors D, E, F, G, L, K (REINHARDT-HANISCH 2008, BOBROWSKI et al. 2021b, 2021c, EHMKE et al. 2024). The phenyl phosphorodiamidate (PPDA) urease inhibitor, marketed as Atmowell[®], is commonly used in cattle farming (EHMKE et al. 2024). In recent years, it has become apparent that an inhibitor based on phosphorodiamidate is favoured (CALVET et al. 2022, EHMKE et al. 2024). Therefore, in these studies, a urease inhibitor composed of a phosphoric acid amide suspended in vegetable oil was used. The inhibitor was manufactured by SKW Stickstoffwerke Piesteritz GmbH.

Taking the above factors into account, the use of a urease inhibitor (UI) was expected to lead to a reduction in ammonia emissions. Investigations using PPDA had reduced ammonia emissions in forced ventilated houses with slatted floors with underfloor storage in cattle farming by 10–31% (BOBROWSKI et al. 2021b) and in pig farming by 20–22% (SCHULTE et al. 2022, 2024). The use of the urease inhibitor in combination with an underfloor scraper resulted in a reduction effect of 68% (HAGENKAMP-KORTH et al. 2023). However, these studies above did not consider greenhouse gases and odour emissions. There are only a few studies that also focus on the effects of UI on other emissions (SVANE et al. 2020); there are no systematic studies on effects on other emissions from animal farming.

There are different approaches for calculating the effect of a mitigation measure: mixed model approach (LAIRD and WARE 1982, VERBEKE and MOLENBERGHS 2000, SCHULTE et al. 2022, 2024), direct case-control approach or case-control in time approach (INTERNATIONAL VERA SECRETARIAT 2018, BOBROWSKI et al. 2021b, CALVET et al. 2022). Furthermore, the comparative evaluation of different calculation approaches to the emission reduction has not been systematically discussed in the literature.

Three research objectives were pursued in this study: The first objective was to present the measured ammonia, carbon dioxide, methane, nitrous oxide and odour emissions from three fattening pig houses in Germany. Subsequently, the effects of the urease inhibitor on the ammonia emissions will be calculated and compared using four different calculation approaches. Finally, it should be investigated whether the use of UI also has an effect on the other measured gas and odour emissions in addition to ammonia.

Material and methods

Experimental facilities and design

The experiments were carried out in three mechanically ventilated houses for fattening pigs in the northwest of Germany from 2019 to 2020. Farm 1 in this study was the pig house at the teaching and testing centre of the Chamber of Agriculture Schleswig-Holstein in Futterkamp. The second fattening pig house (farm 2) was the experimental and education centre for agriculture Haus Düsse of the North Rhine-Westphalia Chamber of Agriculture in Bad Sassendorf. Finally, farm 3 was the pig house at the performance testing institute for pigs of the Lower Saxony Chamber of Agriculture in Quakenbrück. Two structurally identical compartments were used for the experiments on each farm. All compartments were equipped with a fully slatted concrete floor and an under-floor slurry pit.

The experimental facilities were similar in terms of equipment and configuration. An overview of the characteristics of the three experimental facilities and their farming methods are shown in Table 1.

Table 1: Characteristics of experimental facilities and farming method

Characteristic (Unit)	Farm 1	Farm 2	Farm 3
Number of animals per compartment	110	88	40
Number of pens per compartment	10	4	4
Space in pen in m ² animal ⁻¹	1.0	0.9	1.0
Window-front orientation	East	South	Northeast
Slot share in %	15	14	13.5
Width of the slots in mm	17	17	17
Width of slats in mm	83	83	83
Slurry pit depth in m	0.75	0.75	0.6
Type of feeding	Liquid feed in long trough	Liquid feed in dry-wet feeder	Dry feed in feeding station via a transponder
Ventilation system	Negative pressure; regulation via temperature-dependent ventilation curve	Negative pressure; regulation via temperature-dependent ventilation curve	Negative pressure; manually regulated by barn staff

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Characteristic (Unit)	Farm 1	Farm 2	Farm 3
Feeding times during the day	5 (sensor controlled)	Ad libitum	Daily rationing
Fresh air regulation	Jet ventilation with 14 fresh air dampers	Trickle ceiling	Trickle ceiling
Animal genetics	Porkuss (Danbred) x German Pietrain, TN70 (Topigs Norsvin) x TN Select	TN70 x PIC408 (Pig Improvement Company), Viktoria (Federal Hybrid Breeding Program) x PIC408	TN70 x Pietrain
Gender	Male and female	Castrates and female	Castrates and female

The experimental periods were divided over the year to take account of different seasonal climatic conditions. Six experimental periods were carried out on farm 1 and farm 2, and four on farm 3. The experimental design, i. e. case-control (in time) approach, has been described in previous publications (HAGENKAMP-KORTH et al. 2015a, BOBROWSKI et al. 2021c, SCHULTE et al. 2022, 2024). Accordingly, one compartment in each farm was used as a control in which no UI was applied. In the treatment compartment, the UI was applied daily over three days during the application phase. The treatment and control compartments were alternated for every second experimental period on farm 1, and for each experimental period on farm 2 and farm 3. For the analysis, the data from both compartments were used in the pre-phase 24 hours immediately prior to the first application of the inhibitor and in the application phase 25 to 72 hours after the first application (application days 2 and 3). A total of 829 hours were evaluated on farm 1, 853 hours on farm 2, and 565 hours on farm 3. The experimental design was deliberately structured to facilitate the application of the chosen calculation approaches.

The data collected for this publication was gathered as part of extensive experiments, the experimental conditions of which have been described in detail in previous studies (SCHULTE et al. 2022, 2024). Therefore, only a short overview of the experimental periods on the three farms are presented in Table A1 in the Appendix.

Urease inhibitor application

The UI used was a phosphoric acid amide UI suspended in vegetable oil. The UI was provided by the company SKW Stickstoffwerke Piesteritz GmbH. The target dose level of the UI was 50 mg m⁻² and the volume of application liquid was fixed at 0.15 l m⁻². In the experiments, the UI was applied on the slatted floor of the compartments using a mobile backpack sprayer (SCHULTE et al. 2022). The UI was applied daily during the application phase in the case compartment. The application took place on farm 1 between 7:15 a.m. and 8:15 a.m., on farm 2 between 8:15 a.m. and 9:15 a.m., and on farm 3 between 9:00 a.m. and 11:00 a.m.

The backpack sprayer application technique has been proved to be effective in previous studies in cattle and pig houses (HAGENKAMP-KORTH et al. 2015a, 2015b, BOBROWSKI et al. 2021a, 2021b, SCHULTE et al. 2022), demonstrating the highest reduction in ammonia emissions (SCHULTE et al. 2024). The procedure and components of backpack sprayer application in pig houses is described in detail in SCHULTE et al. (2022) and is not outlined here.

Emissions measurements and side parameters recorded

Gas concentrations and ventilation rates were required to calculate emissions. Carbon dioxide, ammonia, methane and nitrous oxide concentrations were detected using a Gasetm™ CX4000 Fourier-transform infrared spectroscopy analyser (Gasetm Technologies Inc., Vantaa, Finland). The air rate was determined in the exhaust air shaft on farm 1 and farm 2 using ProVent measuring fans (REVENTA GmbH & Co. KG, Horstmar, Germany), and on farm 3 using the DynamicAir method (Big Dutchman International GmbH, Vechta, Germany). In order to relate emissions to the livestock unit (LU), the number of animals and the animal weight were also recorded. The animal weights were measured on farm 1 and farm 3 using individual animal scales and on farm 2 using group animal scales. On all farms, manure was stored underground in a manure pit throughout the fattening cycle.

A detailed description of the calibration procedure, measuring points, devices and measuring frequency of the parameters relevant to the calculation of emissions for farm 1 and farm 2 is described in SCHULTE et al. (2024), and for farm 3 in SCHULTE et al. (2022).

Odour emissions were recorded discontinuously on farm 1 and farm 2, and no odour measurements were carried out on farm 3. The odour measurements were carried out in the application phase in both the control and UI application compartments. For each experimental period, there were three sampling times per day, each with duplicate determinations, which were then averaged. These samples were collected in the morning between 4:57 a.m. and 6:05 a.m. before the animals became active, around midday between 11:53 a.m. and 1:55 p.m., and in the late afternoon between 4:05 p.m. and 6:46 p.m. Only one odour sample was taken at midday on farm 1 in experimental period 6 and on farm 2 in experimental periods 5 and 6. In total, 60 odour samples were collected.

Duplicate odour sampling was carried out analogously to the sampling of the gas measurements in the bypass of the Teflon® sampling lines of the FTIR using negative pressure. The duration of odour sample collection was 30 minutes. The samples for the control and treatment compartments were taken one after the other. A total of 60 samples were collected, which resulted in 30 odour emission data by averaging the duplicate determinations. The air to be tested was led into odourless nalophane sampling bags. After sampling, the bags were stored in opaque containers and were analysed olfactometrically in the laboratory within a maximum of 30 hours. Internal quality assurance measures carried out by the measuring institute ensure that the results are not influenced by the method used to collect and analyse the samples. This procedure corresponds to that of VDI 3880 and DIN EN 13725 (VDI 2011, DIN 2022).

Emissions data processing and statistical analysis

Data processing

All raw data was subjected to a visual plausibility check. More than 99% of the raw data was included for further analysis. Normalisation steps were carried out with the raw data collected: the ammonia concentration was normalised to dry air and converted from ppm to mg m^{-3} ($T = 0 \text{ }^\circ\text{C}$, $p = 1013 \text{ mbar}$). The airflow rate was normalised using the ideal gas equation ($T = 0 \text{ }^\circ\text{C}$, $p = 1013 \text{ mbar}$) (BUNDESMINISTERIUM FÜR UMWELT, NATURSCHUTZ AND NUKLEARE SICHERHEIT 2021). The hourly emissions in $\text{g h}^{-1} \text{LU}^{-1}$ were calculated from this data (SCHULTE et al. 2022, 2024). These steps were retained for ammonia emissions analysis and identically adopted for the carbon dioxide, methane and nitrous oxide emissions in this study.

For the concentration values of all gas emissions below the instrument-specific quantification limit, but above the FTIR detection limit, the value was set to 0.5 times the quantification limit; measured values below the detection limit were accepted as such (Table A2 in the Appendix). For carbon dioxide, ammonia and methane emissions, the affected values were negligible (< 1%). With regard to nitrous oxide emissions, around 60% of the values on farm 1, 99% on farm 2, and 25% on farm 3 were affected.

A plausibility check was also carried out on data for odour emissions. As for the gas emissions, the odour concentrations were multiplied by the air flow rate to give the odour units (OU_E). The odour units were calculated for the respective LU as $OU_E \text{ s}^{-1} \text{ LU}^{-1}$.

Different calculation approaches to investigate the effects on emissions through urease inhibitor application

In this study, four different approaches were used to analyse the effects of the UI on emissions: linear mixed model, direct case-control, case-control in time and ratio-difference. These calculated percentage effects of the UI could be either positive or negative. A calculated negative effect corresponds to a reduction in emissions due to the treatment. The ratio-difference approach is a new approach developed in this study that combines the case-control in time and the direct case-control approach without additionally using a model.

- **Linear mixed model:** The first approach involved a linear mixed model with repeated measurements for the gas emissions across all farms and experimental periods, as given below in Equation 3. The dependent variable y consists of the observed values for every gas, respectively, but each gas was analysed in a separate model of the same kind. Data values gathered in application phase were divided by the corresponding reference values from the pre phase. The variable y resulted in a relative difference and has no unit, and a value of 1 corresponds to 100% of the emissions level of the reference phase (SCHULTE et al. 2022, 2024). The model included the general mean μ , the fixed effects for farm F with $i = 3$ levels, urease inhibitor treatment UI with $j = 2$ levels, experimental phase PH with $k = 2$ levels, and the interaction between phase and treatment ($UIPH$), as well as a random effect for compartments C with $l = 4$ levels within farm and experimental period. Individual hourly measurements were denoted with the index n . The repeated measures within the individual compartments per farm and experimental period were considered to be correlated with a first-order autoregressive covariance structure. The model compared emissions during the application phase with those of the pre-phase for each compartment and calculated a relative value. Finally, the relative values from the control and UI application compartments were compared in order to determine the effect of the UI (SCHULTE et al. 2022, 2024). The necessary comparisons were performed with post hoc t-tests at a global significance level of 0.05, and p-values were adjusted for multiple pairwise testing using a simulation approach in the MIXED procedure in SAS version 9.4 (SAS Institute Inc., Cary, USA).

$$y_{ijklmn} = \mu + F_i + UI_j + PH_k + (UI \cdot PH)_{jk} + C_{ilm} + \varepsilon_{ijklmn} \quad (\text{Eq. 1})$$

- Direct case-control: The direct case-control approach enabled emission comparisons between a compartment with UI application and a control compartment without UI application in parallel time. The identical compartments allowed a simultaneous case-control comparison. The effect of the UI application was determined as the mean difference between the emission values over all experimental periods. The repeated experimental periods allowed the different treatments to be performed alternately in the different compartments (INTERNATIONAL VERA SECRETARIAT 2018, CALVET et al. 2022).

$$Effect (\%) = \left[\left(\frac{E_{case;t_t} - E_{control;t_t}}{E_{control;t_t}} \right) \right] \times 100 \quad (Eq. 2)$$

$E_{case;t_t}$: Hourly average value of emissions in the UI application compartment in the application phase over all experimental periods ($g\ h^{-1}\ LU^{-1}$)

$E_{control;t_t}$: Hourly average value of emissions in the control compartment in the application phase over all experimental periods ($g\ h^{-1}\ LU^{-1}$)

- Case-control in time: Because the ammonia emission reduction effect of a UI application is a relatively prompt on and off reaction, the effect of the UI could also be investigated using the case-control in time approach. The emissions comparison of each compartment used the emissions from the days prior to the first application in the pre-phase (reference time frame to calculate the control values) and the emissions during the UI application in the application phase (reference time frame to calculate the case-values) (INTERNATIONAL VERA SECRETARIAT 2018, BOBROWSKI et al. 2021b).

$$Effect (\%) = \left[\left(\frac{E_{case;t_t} - E_{case;t_c}}{E_{case;t_c}} \right) \right] \times 100 \quad (Eq. 3)$$

$E_{case;t_t}$: Hourly average value of emissions in the UI application compartment in the application phase over all experimental periods ($g\ h^{-1}\ LU^{-1}$)

$E_{case;t_c}$: Hourly average value of emissions in the UI application compartment in the pre-phase over all experimental periods ($g\ h^{-1}\ LU^{-1}$)

- **Ratio-difference:** The ratio-difference approach is a novel approach that was developed and used for the first time in the current study. It combines the case-control in time and the direct case-control approach without the additional use of a statistical model. For this purpose, the ratios between emissions of the control and UI application compartments were first separately calculated for the application phase and pre-phase. Thereafter, the difference between the ratios in the application phase and the pre-phase was calculated.

$$Effect (\%) = \left[\left(\frac{E_{case;t_t}}{E_{control;t_t}} \right) - \left(\frac{E_{case;t_c}}{E_{control;t_c}} \right) \right] \times 100 \quad (Eq. 4)$$

$E_{case;t_t}$: Hourly average value of emissions in the UI application compartment in the application phase over all experimental periods ($g\ h^{-1}\ LU^{-1}$)

$E_{control;t_t}$: Hourly average value of emissions in the control compartment in the application phase over all experimental periods ($g\ h^{-1}\ LU^{-1}$)

$E_{case;t_c}$: Hourly average value of emissions in the UI application compartment in the pre-phase over all experimental periods ($g\ h^{-1}\ LU^{-1}$)

$E_{control;t_c}$: Hourly average value of emissions in the control compartment in the pre-phase over all experimental periods ($g\ h^{-1}\ LU^{-1}$)

The effects of UI application on carbon dioxide, ammonia and methane emissions were investigated using all four approaches. The effects on odour emissions could only be shown in the direct case-control approach, since no odour emissions were determined in the pre-phase. The t-test was used to test the calculated mitigation effects from the direct case-control, case-control in time and ratio-difference approaches against 0 and to get an estimate for the mean mitigation effect along with its 95% confidence interval (thus testing at a significance level of 0.05). These tests analysed the difference between the emissions in the case and control compartments in the direct case-control approach, and the difference between the emissions in the application phase and pre-phase in the case compartment in the case-control in time approach. For the gases, the data were the means of each experimental period, while for odour the data were the individual 60 odour samples. The results from these mean calculations along with their confidence intervals could then be compared to the means and confidence intervals from the mixed linear models. The narrower the confidence intervals, the more precise and therefore also more useful the mean estimates were; hence this was selected as the criterion for the evaluation of the different approaches.

For comparison reasons, the same mixed linear model was also used without all farm-related effects and restricted to data from each individual farm, respectively.

Results

Experimental conditions

The relevant experimental conditions are shown in Figure 1, and include the hourly average compartment temperature ($^{\circ}\text{C}$), the ventilation rate ($\text{m}^3 \text{ animal}^{-1} \text{ h}^{-1}$), livestock unit (LU) and compartment humidity (%) in the pre-phase over all experimental periods for control and treatment compartments on each farm. It can be seen that the values of all parameters were very similar between the control and treatment compartments for each respective farm. However, these conditions varied between the farms. On farm 3, the average compartment temperature was almost 5°C higher than on the other two farms. In addition, the ventilation rate on farm 3, at $55.8\text{--}58.1 \text{ m}^3 \text{ animal}^{-1} \text{ h}^{-1}$, was 44% higher than on farm 1 and 15% higher than on farm 2. Farm 3 had the lowest number of livestock units in its compartments, which corresponds to less than a third compared to farm 1 and less than half compared to farm 2. Compartment humidity on farm 3 had an average value of 60.1% compared to farm 1 (66.5%) and farm 2 (54.5%) (Figure 1, Table A1 in the Appendix). The reasons for farm 3 having the highest compartment temperature, highest ventilation rate and lowest livestock unit can be explained by the manual regulation of compartment temperature at higher temperatures, the smallest pen size, the lowest average weight of the animals and the occurrence of half of experimental periods in the summer season (SCHULTE et al. 2022, 2024). The compartment temperature on farm 2 is on average slightly higher than on farm 1, while the ventilation rate on farm 2 was 18% higher and the humidity 20% lower than on farm 1. These correlations may indicate that warmer conditions prevailed in the compartments on farm 2, which in turn could be explained by the orientation of the window front toward the south (Figure 1, Table A1 in the Appendix).

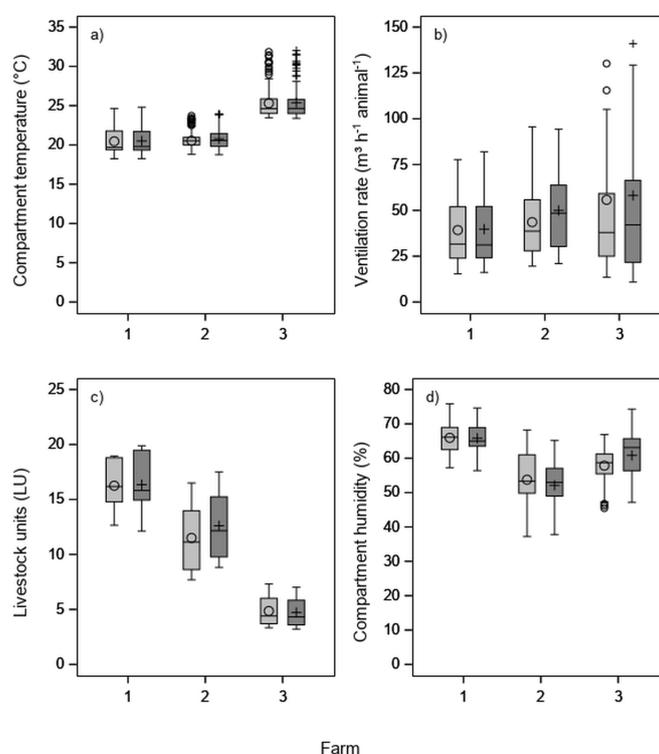


Figure 1: Average hourly a) compartment temperature ($^{\circ}\text{C}$), b) ventilation rate ($\text{m}^3 \text{ h}^{-1} \text{ animal}^{-1}$), c) livestock unit (LU) and d) compartment humidity (%) in the pre-phase in the control (o) and UI application (+) compartments over all experimental periods for each farm

Emissions values

Table 2 presents the hourly average emissions of carbon dioxide, ammonia, methane and nitrous oxide ($\text{g h}^{-1} \text{LU}^{-1}$) in the control compartments by farm over the entire experimental period. On farm 1, 413 hourly average values were taken into account, with 427 values on farm 2 and 288 values on farm 3.

The emission levels of carbon dioxide, ammonia and methane differed between the farms. For ammonia and methane emissions, it can be assumed that the increased values were due to the increased compartment temperature and thus presumably also higher slurry temperature. Since most carbon dioxide emissions are primarily caused by animal respiration, the experimental conditions cannot be the reason in this case.

Table 2: Hourly average carbon dioxide, ammonia, methane and nitrous oxide emissions ($\text{g h}^{-1} \text{LU}^{-1}$) in the control compartment by farm across the entire experimental period (mean \pm standard deviation); N indicates the number of hours evaluated

Farm	Carbon dioxide	Ammonia	Methane	Nitrous oxide	N
Farm 1	380 \pm 82	1.8 \pm 0.3	11.0 \pm 2.4	0.004 \pm 0.066	413
Farm 2	602 \pm 123	2.3 \pm 0.3	6.7 \pm 2.3	0.001 \pm 0.001	427
Farm 3	544 \pm 104	2.8 \pm 0.8	14.2 \pm 7.3	0.005 \pm 0.058	288

The odour data was only determined for farm 1 and farm 2. Table 3 shows the results of the odour emissions from the control compartment in the application phase. The results for odour emissions per LU are very similar, at 81 $\text{OU}_E \text{ s}^{-1} \text{LU}^{-1}$ on farm 1 and 83 $\text{OU}_E \text{ s}^{-1} \text{LU}^{-1}$ on farm 2.

Table 3: Average odour emissions ($\text{OU}_E \text{ s}^{-1} \text{LU}^{-1}$) in the control compartment in the application phase by farm across all experimental periods (mean \pm standard deviation); N indicates the number of measurements evaluated

Farm	Odour emissions ($\text{OU}_E \text{ s}^{-1} \text{LU}^{-1}$)	N
Farm 1	81 \pm 31	16
Farm 2	83 \pm 75	14

Effects of different calculation approaches on emissions related with urease inhibitor application

Four different calculation approaches were used to investigate the effects on emissions: linear mixed model, direct case-control, case-control in time and ratio-difference (Table 4, Table A3 in the Appendix). A detailed description of these approaches can be found in the “Material and methods” chapter. The effects of UI application were analysed both per farm and across all farms. The effects on odour emissions could only be shown using the direct case-control approach because no odour emissions were determined in the pre-phase.

The effect of the UI on carbon dioxide emissions was investigated using all approaches on all farms. There was no clear trend towards a negative or positive effect for carbon dioxide. However, there was a clear effect on ammonia emissions over all farms; all calculation approaches showed a significant effect between -22% and -24% ($p < 0.05$).

Different calculation results were obtained for methane emissions. The calculation using the direct case-control approach showed a positive effect of $+10\%$ of methane emissions across all farms. However, the significant effect on farm 2 ($+31\%$) cannot be attributed to the UI due to the different levels of

methane emissions in the control and UI application compartments in the pre-phase and the fact that this is not taken into consideration in the direct case-control approach (Table A4 in the Appendix). All other approaches showed neither clearly positive nor clearly negative effects.

Odour emissions were only determined on farm 1 and farm 2 and calculated using the direct case-control approach. The effects are not significant, meaning that neither positive nor negative effects could be identified.

Table 4: Effects of the urease inhibitor application on the measured carbon dioxide, ammonia, methane and odour emissions for each different calculation approach (negative values mean a reduction effect; effects statistically tested with t-test; no marker shows no significance; * = $p < 0.05$); (Lower and upper 95 % confidence interval limits)

Emission	Farm	Linear mixed model ¹⁾ Effects in %	Direct case-control approach ²⁾ Effects in %	Case-control in time approach ³⁾ Effects in %	Ratio-difference approach ⁴⁾ Effects in %
Carbon dioxide	1	±0 (-6; +5)	±0 (-10; +9)	+4 (-14; +21)	±0 (-3; +3)
	2	-4 * (<0; -8)	+1 (-8; +11)	-3 (-5; ±0)	-2 (-7; +2)
	3	-6 (-46; +34)	+1 (-26; +28)	-7 (-18; +4)	-5 (-17; +6)
	1-3	-3 (-7; ±0)	+1 (-5; +6)	-1 (-7; +5)	-2 (-5; ±0)
Ammonia	1	-17 * (-4; -30)	-19 * (-5; -33)	-18 * (-4; -33)	-19 * (-10; -29)
	2	-29 * (-26; -32)	-25 * (-9; -41)	-23 * (-15; -30)	-27 * (-15; -40)
	3	-19 * (-6; -33)	-21 * (-4; -37)	-26 * (-9; -44)	-22 * (-1; -44)
	1-3	-24 * (-22; -26)	-22 * (-15; -29)	-23 * (-16; -28)	-23 * (-17; -29)
Methane	1	+2 (<0; +4)	+2 (-24; +28)	-4 (-24; +16)	±0 (-7; +7)
	2	-3 (-13; +6)	+31 * (+8; +52)	+3 (-7; +12)	±0 (-5; +4)
	3	-3 (-22; +16)	-7 (-66; +53)	+3 (-19; +24)	-2 (-15; +10)
	1-3	±0 (-7; +8)	+10 (-6; +26)	±0 (-7; +8)	±0 (-4; +3)
Odour	1		+20 (-12; +51)		
	2		+1 (-11; +13)		
	1-2		+11 (-6; +28)		

¹⁾ Linear mixed model: The first approach is a linear mixed model with repeated measurements separately for the gas emissions over all farms and experimental periods. The model included fixed effects for farm, phase, treatment and the interaction between phase and treatment, and a random effect for compartments for each farm and experimental period (SCHULTE et al. 2022, 2024). Results for individual farms were estimated with a similar model but without farm effect, with the data of each individual farm only.

²⁾ Direct case-control approach: The direct case-control approach makes it possible to compare the emissions between a compartment with UI application and a control compartment without UI application parallel in time. The identical compartments allowed a simultaneous case-control comparison. (CALVET et al. 2022, INTERNATIONAL VERA SECRETARIAT 2018).

³⁾ Case-control in time approach: The comparison of emissions in each compartment used the emissions from the days prior to the first application in the pre-phase (reference time frame to calculate the control values) and the emissions during the UI application in the application phase (reference time frame to calculate the case values) (BOBROWSKI et al. 2021b, INTERNATIONAL VERA SECRETARIAT 2018).

⁴⁾ Ratio-difference approach: The ratio-difference approach combines the case-control in time and the direct case-control approach. For this purpose, the ratios between emissions of the control and UI application compartments were first calculated separately for the pre-phase and application phase. Thereafter, the difference between the ratios in the application phase and the pre-phase was calculated.

Discussion

Experimental design and emission measurement

The compartments on all three farms are mechanically ventilated and fully slatted compartments with under-floor manure storage. At more than 81 %, this is the most widespread and typical farming method in fattening pig farming in Germany (STATISTISCHES BUNDESAMT 2021).

Figure 1 and Table A1 in the Appendix show the experimental conditions for the compartment temperature, ventilation rate, livestock units and compartment humidity per farm and control and treatment compartments. The values of the parameters per farm are very close to each other between the control and treatment compartments in the pre-phase. This provides the conditions that allow a comparison between the two compartments on each farm. However, the experimental conditions varied between the farms. This showed that a range of experimental conditions had already been taken into account in these experiments. Nevertheless, extending the experiments on other farms could yield further insights.

During the application phase, the UI was applied daily using a backpack sprayer. This application technique was used in previous studies and provided the maximum effect on ammonia emissions (SCHULTE et al. 2022, 2024). This technique should thus ensure that the effect of the UI was maximised so that the effects on the other emissions could be optimally analysed.

Carbon dioxide, ammonia, methane and nitrous oxide emissions were measured using a FTIR spectrometer. This is an established device for measuring gaseous emissions and has been used in previous investigations (TABASE et al. 2020, BOBROWSKI et al. 2021c, SCHULTE et al. 2022, 2024). Emission values below the device-specific quantification limit cannot be measured correctly. The procedure for dealing with these values in this study were described above in the section Material and methods. A different procedure is conceivable, for example, not considering all values below the limit of quantification. No systematic description of this or other approaches to dealing with this issue could be found in the literature. Both procedures lead to distortions and reduce the informational value. If these values are not taken into account, this will also lead to measurement gaps in the data set. Systematic research is needed into the effects of the procedure used on emissions. Nevertheless, for carbon dioxide, ammonia and methane emissions, the number of values below the limit of quantification of the FTIR were negligible (< 1 %). For nitrous oxide emissions, these included around 60 % of the values on farm 1, 99 % on farm 2, and 25 % on farm 3. The adjustment of the measured values resulted in negative emissions for nitrous oxide when offset against the background concentrations. Although these were the calculated values, they cannot correspond to reality. Thus, an FTIR does not appear to be the most appropriate tool for determining nitrous oxide concentrations when they are as low as in this study.

Odour emissions were recorded discontinuously on farm 1 and farm 2, and no odour measurements were carried out on farm 3. For each experimental period, three sampling times were planned as duplicate determinations on the day. The air to be tested was directed into sampling bags and analysed olfactometrically in the laboratory. This procedure corresponds to that of VDI 3880 and DIN EN 13725 (VDI 2011, DIN 2022). However, the discontinuous measurement method does not allow a complete temporal analysis of the emissions, as the samples were only taken at three points in time during the day. The financial and human resources required for these measurements were very high. The available resources did not allow a higher measurement resolution. In contrast to the gas emissions discussed above, which can be measured objectively and continuously using FTIR, for

example, the subjective component of odour perception complicates the determination and further development of a suitable continuous method for higher data frequency (UBEDA et al. 2013).

As described in the results, there were differences in the levels of carbon dioxide, ammonia, and methane emissions between the farms (Table 2). The reasons for these differences were not analyzed in detail in this study. Various explanations can be derived from the literature, such as the relationship between the orientation of the window front and compartment temperature or the influence of the type of feeding, which would need to be investigated separately in further analyses (CHEN et al. 2025, HBLFA and BOKU 2025, KECK 1997).

The average gas emissions in the control compartment over the entire experimental period for carbon dioxide were $506 \text{ g h}^{-1} \text{ LU}^{-1}$, for ammonia $2.2 \text{ g h}^{-1} \text{ LU}^{-1}$, for methane $10.2 \text{ g h}^{-1} \text{ LU}^{-1}$ and for nitrous oxide $0.003 \text{ g h}^{-1} \text{ LU}^{-1}$ (Table 5). The data in this study corresponds to the values of emissions from the literature as well as the general variation given in the literature, even if the nitrous oxides in this study appear to be very low.

Table 5: Carbon dioxide, ammonia, methane and nitrous oxide emissions ($\text{g h}^{-1} \text{ LU}^{-1}$) in the control compartment over the entire experimental period in slatted and mechanically ventilated fattening pig houses in this study (own data) compared with the literature (minimum–maximum; * = Values were converted into the study unit ($\text{g h}^{-1} \text{ LU}^{-1}$))

Carbon dioxide	Ammonia	Methane	Nitrous oxide	References
506 (203–1157)	2.2 (1.1–5.2)	10.2 (2.3–31.3)	0.003 (–0.291–0.273)	Own data (Control)
661 (592–729)*		1.1 (0.6–1.5)*		Ni et al. (2008)
682 (655–707)	1.4 (1.4–1.5)	6.3 (2.3–11.5)	0.052 (0.006–0.093)	NGWABIE et al. (2011)
	1.7 (0.4–6.1)	7.9 (0.4–26.9)*	0.089 (0.000–0.296)	WANG et al. (2017)

Measuring odour emissions from pig houses is a complex process which is influenced by many factors, including building construction, ventilation system, feed composition, manure storage and removal, topography and weather conditions (RZEŹNIK and MIELCAREK-BOCHEŃSKA 2022). In addition, odour emissions are dependent on animal activity and thus the measurement timing of a discontinuous method such as olfactometry must be taken into account (ROMAIN et al. 2013). Together, this means that measured odour emissions from pig houses can be highly variable. This became clear through comparisons with the literature (Table 6). The odour emissions in the control compartments in this study across farm 1 and farm 2 were $82 \text{ OU}_E \text{ s}^{-1} \text{ LU}^{-1}$.

Table 6: Odour emissions ($\text{OU}_E \text{ s}^{-1} \text{ LU}^{-1}$) of fattening pigs in slatted and mechanically ventilated houses in this study (own data) compared with the literature (minimum–maximum)

Odour emissions	References
82 (16–293)	Own data (control)
50	VDI (2011)
89 (17–225)	MIELCAREK and RZEŹNIK (2015)
139 (76–254)	ÖTTL et al. (2018)

Effects on emissions using different calculation approaches for the urease inhibitor application

There are different approaches calculating the effects on emissions in the literature: linear mixed model, direct case-control and case-control in time (INTERNATIONAL VERA SECRETARIAT 2018, BOBROWSKI et al. 2021b, CALVET et al. 2022, SCHULTE et al. 2022). No studies have systematically compared these calculation approaches. In addition, a novel ratio-difference approach was applied in this study (see Material and methods). While these approaches were primarily aimed at analysing ammonia emissions, they were also adopted for analysing the other emissions in this study. The calculation approaches differed in their temporal and spatial considerations and in the additional factors (Table 7).

Table 7: List of the calculation approaches and their respective consideration of multiple compartments, multiple phases and additional factors

Calculation approach	Consideration of multiple compartments	Consideration of multiple phases	Consideration of additional factors
Direct case-control	X		
Case-control in time		X	
Ratio-difference	X	X	
Linear mixed model	X	X	X

In a theoretical optimum state, when considering a control and a UI application compartment in a pre-phase and an application phase, all emissions would be identical except for those in the UI application compartment during the application phase. In this case, the results of the direct case-control, case-control in time and ratio-difference calculation approaches would be identical. However, the reality often deviates from this optimum state so that different results are obtained.

In the direct case-control approach, the emissions were compared between the control and UI application compartments in the application phase. If there is a different initial level between the compartments, the direct case-control approach may overestimate or underestimate the effect of a measure. In this study, this issue was particularly evident in the direct case-control approach on farm 2 for methane emissions (Table 4). Due to the differing emission levels in the two compartments in the pre-phase, this approach resulted in a significant reduction which is likely not attributable to the UI. Table A4 in the Appendix shows that methane emissions were almost 35% higher in the UI application compartment compared to the control compartment on farm 2 during the pre-phase without the use of UI. The reduction effects on methane emissions due to the UI were underestimated on farm 2 (Table 4). There may be many reasons for the different emission values in the control compartments, although every attempt was made to ensure that the compartments were equipped and managed as identically as possible. This included structurally identical and equivalently equipped compartments, as well as uniform climate and feeding management. In addition to compartment temperature, other factors can influence methane emissions in particular, including the retention time of the slurry in the compartment or the cleanliness of the slurry pits (HAEUSSERMANN 2006). Furthermore, there are a number of other approaches to regulating methane emissions (NI et al. 2008, NGWABIE et al. 2011, WANG et al. 2017). However, not all influencing factors can be controlled. For example, even with identical initial livestock, variations in development may occur due to indi-

vidual differences among animals. Additionally, the compartments' individual locations within the pig house may lead to different incoming and outgoing airflow patterns and external influences, such as varying exposure to sunlight depending on the orientation of the pig house. In the mixed linear model approach, it is possible to add further influencing factors beyond what was done in this study with farm and compartment effects. These could be class factors as for example housing systems or management practices, but also any linear or quasi-linear regression factors could be added in the same line as in analysis of covariance models. The latter may include correction factors, e.g. for barn temperature or for body mass of the animals that could then also provide added benefit of enabling comparisons beyond the current study, since estimates could be made for all values that are permitted to be interpolated within the range of the respective study by using the estimated regression parameters for these correction factors.

In the case-control in time approach, the UI application compartment emissions were compared between the pre-phase and application phase. This approach could also overestimate or underestimate effects if a natural fluctuation in emissions over time is not taken into account. Emissions fluctuate over the course of a day and across seasons, are influenced by special weather events in the short term. When examining temporal intervals of only a few days, it is crucial to include multiples of a full day under each condition. Moreover, the days should be as close together as possible within the same experimental period, but should have enough time between experimental periods to be considered independent in time. The latter also is relevant for the case-control approach.

By selecting the experimental compartments and experimental design, and adapting the management, an attempt was made to minimise the differences in emissions of temporal and spatial considerations in the pre-phase, and thus come close to the optimum state. Nevertheless, there were still differences between the emissions, which could not be explained by this. Therefore, a novel ratio-difference approach was developed, which can be seen as a combination of the spatial consideration of the direct case-control approach and the temporal consideration of the case-control in time approach (Table 7). In this case, the potential problems of the other two approaches, as described above, should be prevented by the ratio calculated from the direct case-control approach of both compartments in the pre-phase and application phase and subsequent case-control in time approach over these ratios of both phases (as presented in Material and methods). The linear mixed model also uses this combination, so that the emission values from both compartments and both phases were considered, even if this model still took additional factors into account (SCHULTE et al. 2022, 2024). In the first three approaches mentioned, all emissions considered were averaged by compartment and phase. The additional factors in the linear mixed model allowed additional information, such as the experimental period or the interaction between phase and treatment, to be taken into account when calculating the effects. However, the effect could only be applied across all farms, and not to each individual farm. The model at hand aims at estimating the overall effect of the emission mitigation, and the farm effects serve as a correction factor of the average emission level. A change in the model structure to nest treatment and experimental phase effects within farms could do that, but would probably lead to an unfair comparison with the other approaches due to using "external" information that the other methods cannot access. It is also possible to remove the farm effects from the model and run it with data of the individual farms only, as shown in Table 4.

When looking at the results for all farms combined, the use of more data than just means of experimental periods allows for smaller confidence intervals when applying a linear mixed model,

specifically when compared to the case-control or case-control in time approaches. This is not surprising, since more data usually lead to smaller standard errors of the mean by definition, but it is also important to mention that this needs to be done in the correct way. It is necessary to consider the correlation over time in the statistical model and not treat the repeated measurements as independent, as this would inflate the degrees of freedom and lead to an overestimation of the experiment's precision. The first-order autoregressive approach used in this study is just one way to do this, depending on the study design and possible missing data different approaches as for example spatial covariance structures might fit better.

Nevertheless, the results of the ratio-difference approach and the linear mixed model differed only slightly. In addition, the ratio-difference approach was relatively simple to calculate, while the linear mixed model requires the use of statistical software and was not directly traceable due to the inclusion of additional factors.

Overall, as described in the results, no systematic differences were found between the results of the different calculation approaches. Therefore, in this study the effects were calculated according to all approaches, and the mean results were used to ensure that the effects were holistically assessed (Table 4).

Previous studies have already been conducted on the effect of UI on ammonia emissions. The hydrolysis of urea from the urine of pigs is catalysed by the enzyme urease. The UI acts to inhibit the urease enzyme so that the hydrolysis of urea and water to ammonium and carbon dioxide is also inhibited. Ammonium is in chemical equilibrium with ammonia (LEINKER 2007, REINHARDT-HANISCH 2008). The expected reduction of ammonia emissions through the use of a UI has been shown in previous studies under different experimental conditions (REINHARDT-HANISCH 2008, Hagenkamp-Korth et al. 2015a, BOBROWSKI et al. 2021b, CALVET et al. 2022, SCHULTE et al. 2022). The effect of the UI on ammonia emissions was also demonstrated in this study. The average reduction effect of ammonia emissions of 22–24% confirmed the appropriate use of the UI and thus enabled an assessment of the effects on further emissions (Table 4).

The results show that the application of the UI had no significant effect on carbon dioxide emissions (Table 4). Individual calculation approaches on the farms led to negative or positive calculated effects. There is a trend towards a minor (–1%), but not significant, mean reduction in carbon dioxide emissions across all farms and across all calculation approaches. According to the chemical reaction equation of urea hydrolysis, a theoretical effect for carbon dioxide can be expected, as carbon dioxide is also a product of urea hydrolysis (KECK 1997). However, the proportion of carbon dioxide from urea hydrolysis is much lower than the proportion produced by the animals' metabolic processes (NOBLET et al. 1989, PEDERSEN and SÄLLVIK 2002, PEDERSEN et al. 2008). Thus, the effect of the UI on the carbon dioxide emissions in the total exhaust air can probably not be identified.

For methane emissions, the results showed very different effects. The average effect across all farms showed a mean value of +3%. These differences can be explained by the natural fluctuations of the emission values. An investigation on biogas and methane production from cattle manure showed no effect from the use of a UI (HAGENKAMP-KORTH et al. 2015c). However, there were also large deviations in the direct case-control approach of +31% on farm 2 (Table 4). These strong effects could not be attributed to the UI. The reason for this was the limitations of the direct case-control approach, which has already been discussed above.

The literature contains a number of procedures for controlling odour emissions. These procedures represent combinations of different principles and locations of action. For example, a distinction is made between reducing odour release using end-of-pipe techniques and improving dispersal (UBEDA et al. 2013), and between dietary manipulations, in-housing management, manure management and end-of-pipe measures (CAO et al. 2023). The results in this study showed two different positive effects of UI on odour emissions. On farm 1 there was a positive effect of +20% and on farm 2 a positive effect of +1%. As described above, odour was measured through discontinuous sampling. In addition, the effect could only be calculated using the direct case-control approach. Accordingly, no effect on odour emissions due to the application of the UI could be demonstrated in this study.

In addition to the emissions described above, nitrous oxide emissions were also measured in order to assess the effect of the UI. Ammonium is also a source of nitrous oxide emissions, so it was reasonable to assume that inhibiting urea hydrolysis would affect nitrous oxide emissions (KHALIL et al. 2009, ZAMAN and BLENNERHASSETT 2010, GAVRILOVA et al. 2019). Unfortunately, due to the low concentrations of nitrous oxide emissions and the quantification limit of FTIR (Table A2 in the Appendix), no statement could be made about the effects of the inhibitor and thus the ammonium degradation on nitrous oxide emissions. This is particularly regrettable with regard to the potential climatic impact, as nitrous oxide has a 265-fold CO₂ equivalence, and therefore even small emissions and their changes could have a major impact (UBA 2025c).

Conclusions

This study measured the emissions of carbon dioxide, ammonia, methane, nitrous oxide and odour from three mechanically ventilated pig houses. The focus was on presenting emissions and comparing the effects of the application of a UI on these emissions by evaluating four different calculation approaches. Based on the findings, the following conclusions were drawn:

- The average gas emissions in the control compartment over the entire experimental period on all three farms studied for carbon dioxide were 506 g h⁻¹ LU⁻¹, for ammonia 2.2 g h⁻¹ LU⁻¹, for methane 10.2 g h⁻¹ LU⁻¹ and for nitrous oxide 0.003 g h⁻¹ LU⁻¹.
- The direct case-control and case-control in time calculation approaches alone risk overestimating or underestimating the effects of the reduction measure. The novel approach of ratio-difference can therefore be recommended, as it is a combination of the two approaches mentioned above, it is simple to calculate and it provided very similar results to the linear mixed model with additional factors in this study.
- The results showed that the use of a combined approach, as a ratio-difference or linear mixed model, can be recommended. However, these approaches require the emission data from the pre-phase and application phase of the UI application and control compartments. It is therefore recommended to adapt the experimental design in the future so that this data can be measured.
- The ratio-difference approach can be applied to combine data from experiments with the same study design and with otherwise comparable conditions. If there are differences that need to be considered, the linear mixed model allows to account for that by adding relevant correction factors. The option to use more data will usually lead to better estimates with lower standard errors compared to methods that make use of simpler calculations with fewer data.

- The application of the UI reduced the ammonia emissions 22–24% on average across all farms and calculation approaches. This finding reinforces the efficacy of UIs for mitigating ammonia emissions in fattening pig houses.
- The results of the effects on odour emissions were contradictory, with a slight increase in one farm and a decrease in another. Due to the discontinuous measurement approach and variability in odour perception, no definitive conclusion about odour could be drawn. The findings also highlight the need for continuous improvements in sampling methods for complex parameters like odour emissions.
- No consistent effects of a UI application on carbon dioxide and methane emissions were found. In the case of carbon dioxide, only a tendency towards reduction was observed, which can also be confirmed by the chemical interactions. The dominance of carbon dioxide from animal respiration likely masks any contribution from urea hydrolysis. Consequently, in future experiments it may be recommended to not investigate the effect of the UI on these two emissions.
- Nitrous oxide has the highest CO₂ equivalent value. Small changes in these emissions have a strong climate-relevant effect. Unfortunately, the effect of the UI on nitrous oxide could not be clarified in this study due to the FTIR measuring technique selected. A systematic investigation into how to deal with values below the limit of quantification should be carried out. A gas analysis technique with a much lower quantification limit is required for future investigations.

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Acknowledgements

The corresponding author would like to thank all participating co-authors and the EmiMin working group for their professional support. Thanks also go to the staff of the experimental facilities for their support during the experiment. Furthermore, the authors would like to thank SKW Stickstoffwerke Piesteritz GmbH for providing the urease inhibitor.

The project is supported by funds of the German Government's Special Purpose Fund held at Landwirtschaftliche Rentenbank (grant number 839 180).