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Research Paper

A urease inhibitor reduces ammonia emission in fattening pigs reared on slatted floor in summer conditions

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Intensive pig farming is a main contributor to ammonia (NH_3) emissions. Urease inhibitors block the conversion of the excreted urea into ammonium and may reduce effectively these emissions at the housing level. This study evaluated the effect of applying a urease inhibitor in a naturally ventilated and fully slatted pig house. Emissions were compared using two approaches: in-time evaluation and case-control approach. Two identical rooms in size and management were used in this experiment. Seventy growing pigs of 70 kg weight were placed in each room. One room was treated with the urease inhibitor EBN (based on phosphorodiamidate) during 12 days (treatment phase) at a rate of 0.17 mL m^{-2} day^{-1}. The study also included a pre-treatment phase of 2 days and a post-treatment phase of 15 days. Temperature and concentrations of NH_3 and carbon dioxide (CO_2) were recorded every 2 min, and then aggregated on an hourly basis. Natural ventilation rate was calculated using the CO_2 balance method. The case-control approach showed more reliable results since only two days were available for the in-time approach. On average, emissions were reduced by 29% over the treatment phase. After each application, the maximum abatement potential was found between 4 and 14 h after application of the inhibitor. This study was conducted under specific farm and climate conditions. More studies are needed to confirm the abatement potential in a wider range of situations.

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Nomenclature

CO_2	carbon dioxide
C_{inlet}	concentration measured at the air inlet (ppm)
C_{outlet}	concentration measured at the air outlet (ppm)
E	emission rate (g animal^{-1} h^{-1})
EBN	"Estabilizante Biostático de Nitrógeno" which is the commercial name of the urease inhibitor based on phosphoramidate
G_{CO_2}	amount of CO_2 produced inside a house (m^3 h^{-1})
LU	livestock unit, an indicator of animal mass equivalent to 500 kg live weight
m	animal weight (kg)
$N_{animals}$	number of animals inside a room
NH_3	ammonia
N_2O	nitrous oxide
ppm	parts per million
V	airflow rate (m^3 h^{-1})
W	Watt
Φ_{total}	total heat production by the animals (W)

1. Introduction

Ammonia (NH_3) emissions in agricultural systems constitute a relevant nutrient loss (Leip et al., 2015), impair ecosystems through eutrophication and nitrification processes (van Grinsven et al., 2015) and have consequences for animal and human health (Drummond, Curtis, Simon, & Norton, 1980; Hristov, 2011). These emissions also contribute indirectly to climate change as nitrous oxide (N_2O) emissions arising from nitrification and denitrification reactions following the NH_3 deposition on the soils (Gavrilova et al., 2019). Livestock housing and on-farm manure management are responsible of a relevant share of ammonia emissions, particularly in countries with high animal population in intensive production systems (EEA, 2021b).

Spain is the second producer of pig meat in Europe, and the fifth producer worldwide (FAOSTAT, 2021). Emissions from Spanish pig farms account for 15.5% of national ammonia emissions according to the national inventory report (EEA, 2021a). Reducing emissions during the next years is mandatory in Europe according to the National Emission Ceilings Directive (European Commission, 2016). Accordingly, Spain has launched a specific regulation (BOE, 2020) to reduce ammonia emissions in pig houses by 30 and 60% reduction with respect to the reference system in existing and new facilities, respectively. Following an integrated approach (Giner-Santonja et al., 2017), effective mitigation strategies consider nutritional measures, farm design and management, manure management and land application. Some of the most effective mitigation techniques reviewed by Giner-Santonja et al. (2017) still need to be tested or validated under usual production conditions in Southern Europe, while some others are difficult to implement in already existing farms.

Using slurry additives such as urease inhibitors could be a part of this integrated mitigation strategy if their cost-effectiveness and practical use is demonstrated under commercial farm conditions. Inside pig houses, most ammonia emissions arise from the urea excreted in urine. It is long known that the enzyme urease plays an essential role in this process because it is responsible of the relatively fast breakdown of urea into ammonium and carbon dioxide (Werner, 1921). However, this process can be delayed by using urease inhibitors. The effectiveness of these substances has been widely studied and demonstrated for urea-based synthetic fertilizers (Cantarella, Otto, Soares, & Silva, 2018; Sigurdarson, Svane, & Karring, 2018). For livestock production, there is evidence of potential use of this technique (Hagenkamp-Korth, Haeussermann, & Hartung, 2015; Varel, 1997), but it has not been evaluated in commercial farm conditions until recently (Bobrowski, van Dooren et al., 2021; Bobrowski, Willink, et al., 2021). These authors reported emission reductions ranging from approximately 20%–70% depending on housing system and climate conditions. Both studies showed lower reductions at higher temperatures. They also found that the mitigation potential was higher in naturally ventilated buildings with solid floors than in mechanically ventilated buildings with slatted floors. Application dose and frequency, as well as slurry removal, could also affect the reported mitigation potential.

The aim of this study was to quantify the ammonia mitigation potential and response in time of using the urease inhibitor EBN (based on phosphorodiamidate) during part of a growing period in a fully slatted fattening pig farm in warm conditions.

2. Material and methods

2.1. Experimental design

Emissions were evaluated using a double approach: in-time evaluation and case -control designs. Two rooms with identical dimensions, management, feeding, and number and age of animals were used for the study. In the control room, no treatment was applied throughout the experiment. In the treatment room, the following application calendar was used. During a first period of two days (pre-treatment phase), no additive was used in order to assess the baseline emission of both rooms under the same conditions; during a second period of 12 days (treatment phase), the additive was applied to the manure pit; finally, a third period of 15 days (post-treatment phase) was monitored in order to evaluate emissions after the treatment stopped.

2.2. Animals and housing

The experiment was conducted in a commercial pig farm located in Hinojosa de Jarque (Teruel, Spain) and had a duration of 29 days (from 6 th July to 3rd August 2020). No other agricultural buildings or slurry lagoons were placed in the prevailing wind directions (East–West).

The building used in this study was 78 m long and 16 m wide, and had eight independent rooms (dimensions 10 × 14.4 m) connected by a lateral corridor (Fig. 1). 140 Large White females with average initial weight of 70 kg were used in the study. Animals were divided into 2 groups of 70 animals each, which were allocated in two adjacent rooms from the

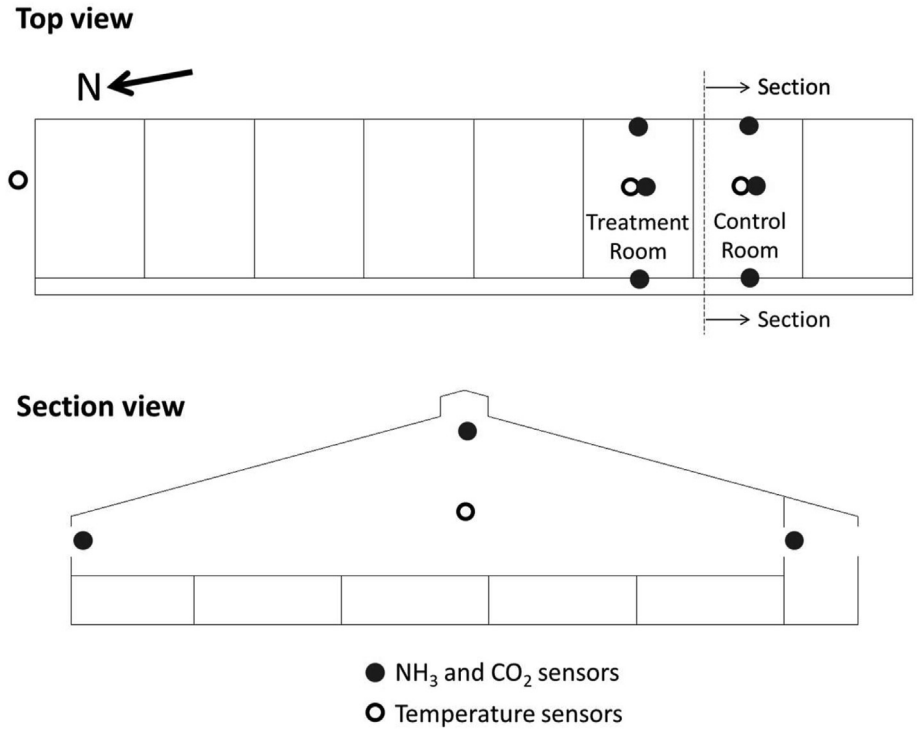

Fig. 1 – Top view and section of the rooms used in the experiment and location of sensors.

eight available rooms in the building. Animals were fed *ad libitum* with a non-medicated commercial feed with the following composition on fresh matter basis: 90% dry matter, 15% crude protein, 6% ash, 5% fat, 4% crude fibre. Fresh water was also provided *ad libitum*.

Rooms had a fully slatted floor, which is the reference system according to Giner-Santonja et al. (2017). The slurry pits of both rooms were not connected and were emptied and cleaned before animals entered. Slurry was accumulated in the pit below the slats during the whole experimental period. Each room had independent natural ventilation with lateral windows and a ceiling ridge. The lateral windows had curtains that were operated automatically by a climate control system depending on the indoor temperature. As the prevailing wind directions were perpendicular to lateral openings and these were relatively small in size, identifying ventilation inlets and outlets was facilitated. No cooling system was installed on the farm.

2.3. *Urease inhibitor and application*

The inhibitor EBN, a phosphorodiamidate (25% w/v) ready-made as a liquid chemical formulation based on propilenglycol that includes stabilizers and antioxidants as additives was supplied by Fertinagro Biotech. The optimised synthesis process and urease inhibitor formulations, together with the necessary application and stability properties, were developed by Fertinagro Biotech. Application dose of the EBN inhibitor was 0.17 mL m^{-2} per day. The liquid-formulated inhibitor EBN was dissolved in water at 0.2% dilution for application. This concentration has no health or environmental implications according to the safety assessment of this additive.

According to previous literature (Hagenkamp-Korth et al., 2015), it was decided to do the application every 24 h in the early morning. Every day during the application phase (from day 3 to day 14 of experiment) application was done manually using a backpack sprayer. Application times were between 7 a.m. and 8 a.m. The application was done only to the slurry underneath the slats, by introducing the nozzle in between the slats. Pigs were present inside the pen during the application of the inhibitor.

2.4. *Environmental parameters*

The farm control system registered ambient temperature, gas concentrations and window opening status every 2 min. Individual data were examined to verify the temporal consistency of the data registered, and then values were integrated into 1-h averages.

The location of sensors is shown in Fig. 1. Three temperature sensors (DOL 114, range 0–60 °C, precision 0.5 °C) were used for this study. Two of these sensors were located inside the rooms (one in the centre of each room at 1.5 m height) and the third sensor was located outside the farm to provide outdoor temperature.

Three ammonia and three carbon dioxide sensors were placed in each room, one next to each window and one near the ridge (Fig. 1). The carbon dioxide sensor was the DOL 19 (Dol Sensors, range 0–10,000 ppm, precision 50 ppm). The ammonia sensor was the FL-6813260 (Draeger, range 0–100 ppm, precision 1.5 ppm). Inlet gas concentrations were provided by the sensors located next to the windows. The inlet and outlet windows changed depending on the direction of wind, and this was identified according to the measured

carbon dioxide measurements at each location. Inlet gas concentration was established as the measurement of those sensors located next to windows which had lowest carbon dioxide concentration.

2.5. Estimation of natural airflow rate and ammonia emissions

Airflow rate was calculated using de carbon dioxide (CO_2) balance method (Pedersen & Sällvik, 2002). This method uses the metabolic CO_2 released by the animals as a tracer to determine ventilation. A mass balance is conducted in which CO_2 production by the animals and the manure is estimated, and on-farm inlet and outlet CO_2 concentrations are used.

The amount of CO_2 produced by the animals was calculated from the metabolic heat produced by the animals following Equation (1) (Pedersen & Sällvik, 2002), and using the equivalence in CO_2 production of 0.200 m^3 per heat production unit (which is 1000 W of metabolic energy) according to (Pedersen et al., 2008):

$$\Phi_{total}(W) = 5.09 \times m^{0.75} + [1 - (0.47 + 0.003 \times m)] \times [5.09 \times m^{0.75} \times (n-1)] \quad (1)$$

where "Φ_{total}" is the total heat produced by the animals (W), "m" is the animal weight (kg) "n" is the ratio between ingested and maintenance energies (Table 2.1. in Pedersen & Sällvik, 2002).

The effect of temperature and animal activity on heat production was also considered following Pedersen and Sällvik (2002) and Pedersen et al. (2008). The animal activity effect was assumed to follow a sinusoidal pattern with a 20% amplitude and minimum activity at 4 a.m. As the slurry pit was empty and clean at the beginning of the experiment, and slurry accumulation was less than one month, it was assumed that slurry did not contribute relevantly to the total CO_2 production. As the study was performed in comparative terms (case vs. control), the potential biases due to estimation of animal heat, effect of animal activity or contribution of slurry to global CO_2 were not expected to affect the aim of this study, which was comparing the effect of the urease inhibitor.

The estimated CO_2 concentration was used to calculate ventilation rate as indicated in Equation (2).

$$V = \frac{G_{CO_2}}{(C_{outlet} - C_{inlet}) \times 10^{-6}} \quad (2)$$

where: V is the airflow rate ($m^3\ h^{-1}$), G_{CO_2} is the amount of CO_2 ($m^3\ h^{-1}$) produced in each room calculated as indicated in this section, C_{outlet} and C_{inlet} are CO_2 concentrations (ppm) measured on farm at the air outlet and inlet, respectively.

Considering that the room was naturally ventilated, openings could act either as inlet or as outlet depending on the wind direction. As indicated before, building orientation respect to prevailing wind directions and disposition of window openings facilitated the identification of inlet and outlet. In addition, CO_2 concentration data were examined and measurement times with inlet concentrations higher than 450 ppm were removed from the analysis. On the other hand, high ventilation rates could derive in low concentration differences which involve high measurement uncertainty in ventilation flow (Calvet et al., 2013). To avoid these inaccurate calculations, a minimum difference between outlet and inlet CO_2 concentration of 100 ppm (two times the sensor precision) was established as selection criterion. As data were further analysed in comparative terms, all information obtained from both rooms at the same time was discarded if this criterion was not met for any of the rooms.

Ammonia emissions were calculated using a mass balance on the farm as in Equation (3).

$$E = \frac{V \times (C_{NH_3\ outlet} - C_{NH_3\ inlet})}{N_{animals} \times 1000} \quad (3)$$

where E is the emission expressed in grams per animal and hour, V is the airflow rate in each room ($m^3\ h^{-1}$) obtained from Equation (2), $C_{NH_3\ outlet}$ and $C_{NH_3\ inlet}$ are outlet and inlet gas concentrations expressed in mg m^{-3} and $N_{animals}$ is the number of animals. For comparison reasons, emissions were also expressed per livestock unit (500 kg live weight).

2.6. Statistical analysis

Summary statistics (average and standard deviation) were calculated for temperature, ventilation rate, ammonia emissions and ammonia emission differences. This information was obtained on an hourly and a daily basis. The comparison between treatment and control was done using two approaches as in Bobrowski, van Dooren et al. (2021). First, an in-time approach was considered, using the pre-treatment phase as reference of the treatment phase in the same room. The second approach consisted in using the control room as reference during the additive application period. As indicated by Bobrowski, Derno, et al. (2021), the first 24 h after the first additive application were not considered in the analysis, which was suggested as the time required to allow emissions to stabilise and provide realistic reference information. In this second approach, statistical differences were evaluated using hourly data from both rooms as a paired t-test (treatment vs. control). This was evaluated using Statgraphics Centurion XVIII.

The case-control approach also allowed to compare the chronological reduction response to inhibitor application in the following hours to the application of the additive. Average emission differences between treatment and control were obtained hour by hour during the additive application phase (except for the first day after application) and represented against the time after additive application.

3. Results

3.1. Environmental data and ventilation

The evolution of indoor and outdoor temperatures during the experiment is shown in Fig. 2. The average outdoor temperature was 21.3 °C and ranged between an absolute minimum of 15.1 °C on day 4 of experiment and 35.8 °C on day 21 of experiment. Outdoor temperatures followed a stable evolution throughout the experiment, with minimum temperatures consistently ranging between 15 °C and 20 °C and maximum temperatures around 30 °C.

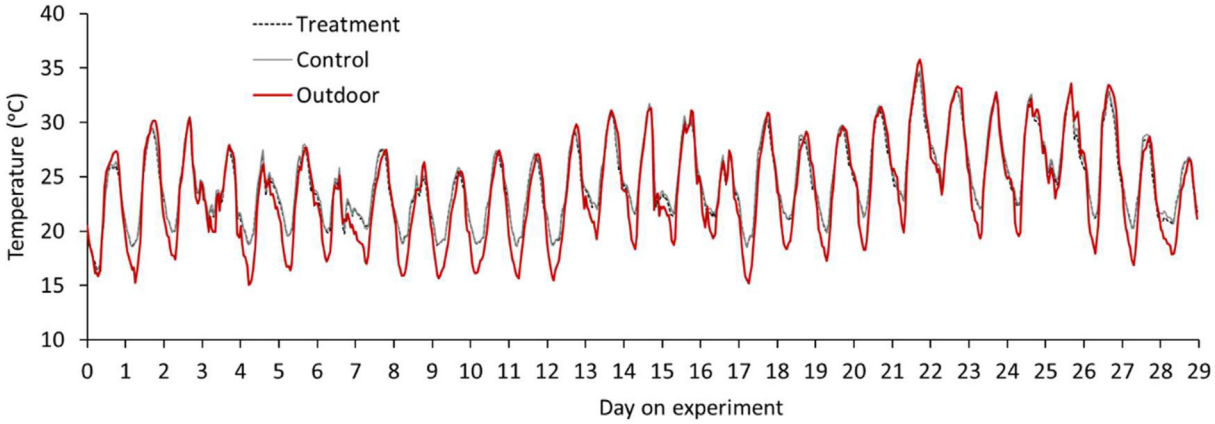

Fig. 2 – Evolution of outdoor temperature and indoor temperatures of control and treatment rooms.

As shown in Fig. 2, the indoor temperature in both rooms followed a similar tendency to the outdoor temperature. No statistical differences were found between control (average temperature 22.8 °C, range from 16.1 to 34.7 °C) and treatment (average temperature 22.6 °C, range from 16.4 to 34.6 °C). The average temperature values inside the rooms in the three phases of the study are shown in Table 1.

The evolution of ammonia and carbon dioxide concentrations measured at the ridge are presented in Fig. 3. These concentrations corresponded with outlet concentrations for most situations during the experiment. The average ammonia concentrations during the experiment were 5.5 and 5.0 ppm in control and treatment rooms, respectively. Maximum concentrations did not exceed 17 ppm. The average carbon dioxide concentrations were 763 and 731 ppm in control and treatment rooms, respectively, and did not exceed at any moment 1400 ppm. Both ammonia and CO_2 concentrations varied during the day according to window opening, and consequently, according to changes in the airflow rate. Average outlet gas concentrations in the three phases of the study are shown in Table 1.

3.2. *Ventilation rate and ammonia emissions*

From the 696 measurement hours of the experimental period, 613 met the criteria of at least 100 ppm difference between outlet and inlet CO_2 concentration. Therefore, 88% of the measured hourly values were considered valid for analysis. The remaining 12% corresponded to situations with high ventilation rates, when CO_2 concentration inside the barn decreased, or situations with low ventilation rates, where inlet and outlet windows could not be identified. The situations of high ventilation occurred more frequently in the afternoon, when windows were completely open due to high temperatures. Table 2 shows the number and percentage of valid data depending on the hour in the day. Night times and early morning had a larger percentage (more than 95%) of valid measurements, whereas this percentage was lower than 70% from 2 p.m. to 4 p.m.

Figure 4 shows the evolution of the airflow rate during the experiment, which ranged between 267 and 2489 $m^3\,h^{-1}\,LU^{-1}$ for the control room and between 292 and 3115 $m^3\,h^{-1}\,LU^{-1}$ for the treatment room. On average, the treatment room had higher ventilation than the control room (1080 vs. 912 $m^3\,h^{-1}\,LU^{-1}$, respectively). Average ventilation rates in the three phases of the study are shown in Table 1.

The evolution of ammonia emission during the experiment is shown in Fig. 4. Hourly ammonia emission ranged from 0.69 to 7.01 $mg\,h^{-1}\,LU^{-1}$ for the control room and between 0.29 and 7.32 $mg\,h^{-1}\,LU^{-1}$ for the treatment room. Minimum emission rates were detected in the early morning, whereas maximum emissions were produced in the afternoon. On average, emissions were higher in the control room (2.84 $mg\,h^{-1}\,LU^{-1}$) than in the treatment room (2.70 $mg\,h^{-1}\,LU^{-1}$). Average ammonia emissions of each room in the three phases of the study are shown in Table 1.

Table 1 – Average room temperature, outlet ammonia and carbon dioxide concentrations, ventilation rate and ammonia emissions during the three monitoring periods.

Variable	Room	Pre-treatment	Treatment	Post-treatment
Temperature (°C)	Control	23.63	23.35	26.15
	Treatment	23.52	23.15	25.90
NH_3 concentration (ppm)	Control	5.01	5.86	4.95
	Treatment	5.62	4.38	4.96
CO_2 concentration (ppm)	Control	720	799	773
	Treatment	693	786	730
Ventilation rate ($m^3\,h^{-1}\,LU^{-1}$)	Control	842	956	873
	Treatment	1038	1093	1037
NH_3 emission rate ($g\,h^{-1}\,LU^{-1}$)	Control	2.89	3.02	2.68
	Treatment	3.75	2.15	2.92

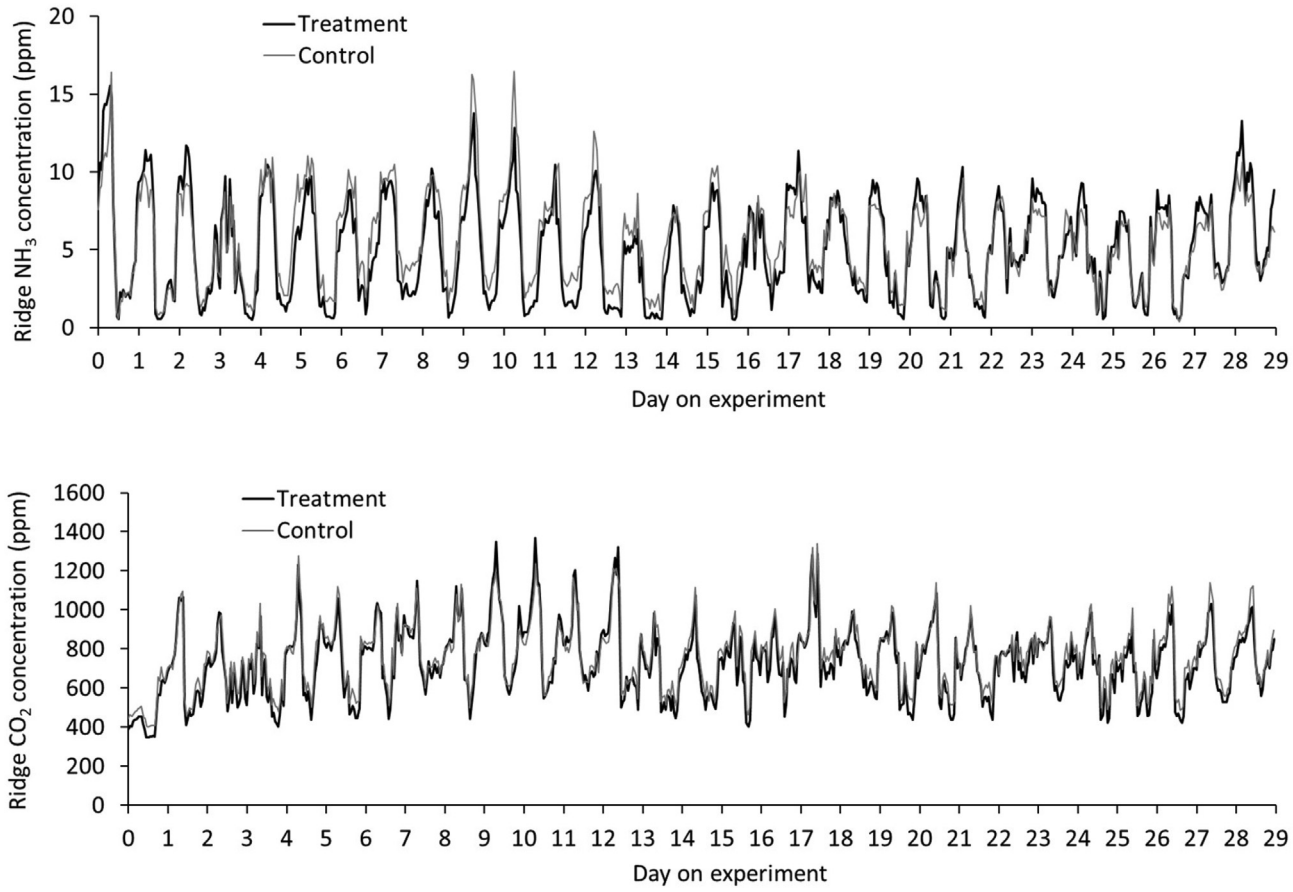

Fig. 3 – Evolution of ammonia (top) and carbon dioxide (bottom) concentrations measured in the ventilation ridge of treatment and control rooms.

Table 2 – Number and percentage of valid ventilation data depending on the hour in the day. A total of 29 measuring days were available.

Hour	Valid	%
0:00	27	93%
1:00	28	97%
2:00	28	97%
3:00	28	97%
4:00	28	97%
5:00	28	97%
6:00	28	97%
7:00	28	97%
8:00	28	97%
9:00	28	97%
10:00	28	97%
11:00	27	93%
12:00	22	76%
13:00	24	83%
14:00	20	69%
15:00	16	55%
16:00	20	69%
17:00	22	76%
18:00	22	76%
19:00	23	79%
20:00	24	83%
21:00	28	97%
22:00	29	100%
23:00	29	100%

3.3. *Effect of the urease inhibitor*

Figure 5 shows the evolution of daily average emissions in control and treatment rooms, as well as the relative difference among them. During the pre-treatment phase no inhibitor was applied in the treatment room and the paired t-test showed that emissions were 29% higher ($p < 0.001$) than in the control room. When the additive was applied (treatment phase), the treatment room had 29% lower emissions than the control room ($p < 0.001$). Urea inhibitor caused a reduction in emissions from the treatment room of 43% with respect to the pre-treatment period, whereas the emissions from the control room did not change relevantly. After the treatment had finished on day 14 of the experiment, emissions from the treatment room increased gradually and were on average 8.6% higher than in from the control room. Compared with the treatment period, the post-treatment period had 36% higher emissions.

Time response to the treatment within a day was explored comparing emissions in the second phase, when treatment was applied. Figure 6 shows the relative difference between treated and control rooms depending on the time (hours) after treatment. Emissions decreased in the treatment room from the moment of application and the reduction with respect to the control room was higher than 30% from 4 to 14 h after

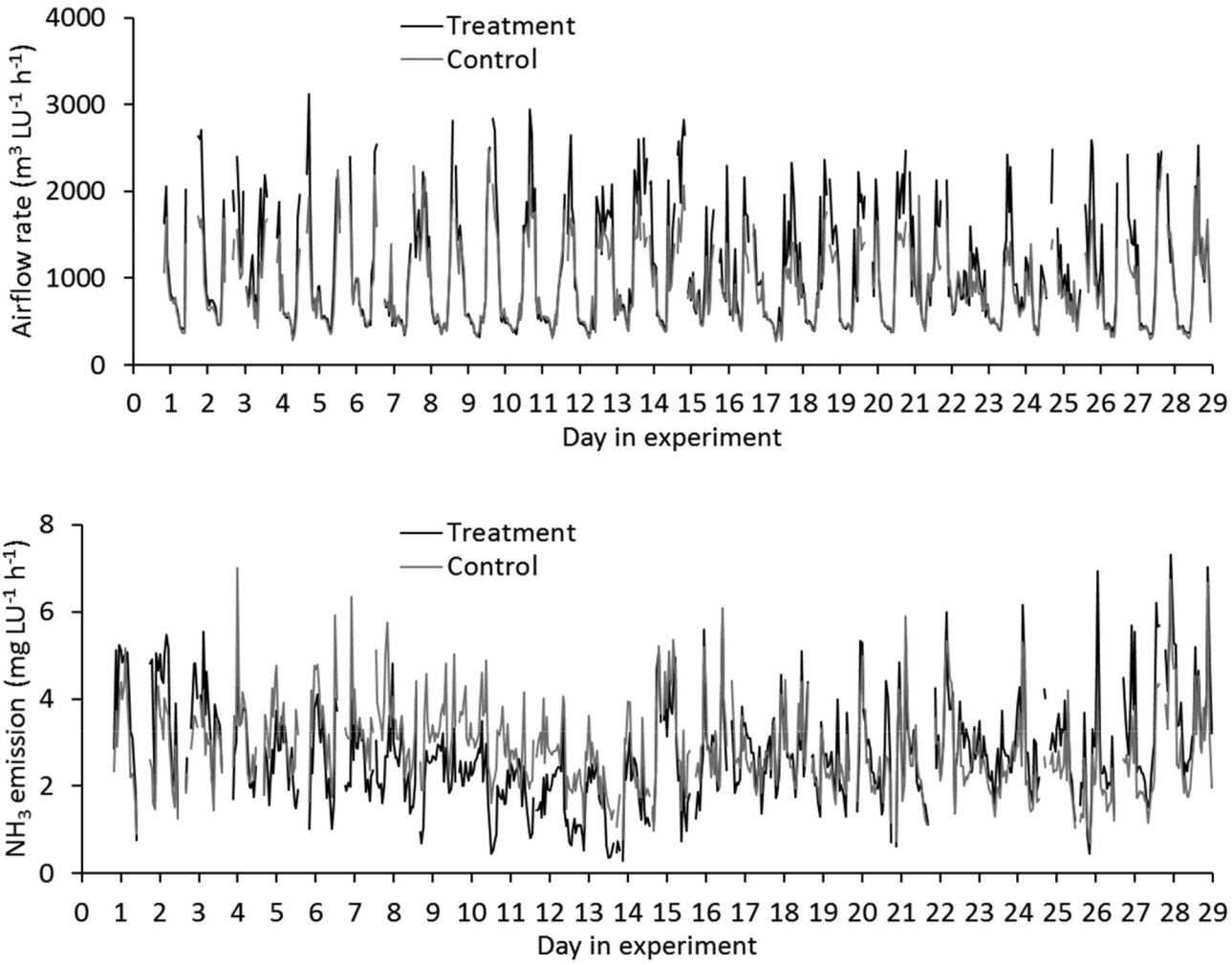

Fig. 4 – Evolution of airflow rate (top) and ammonia emissions (bottom) in control and treated rooms.

treatment. However, this reduction was lower than 20% from 16 h after treatment and decreased to about 10% from 20 h after application. A polynomic regression fitted this tendency ($R^2 = 0.79$) as shown in Fig. 6.

4. Discussion

Although the farm used in this study was not initially designed for emission measurement tests, the selection of the building, rooms and animals allowed the proper development of this experiment. No particular situations in climate, health or productivity occurred that could affect the results. Since the two rooms operated in parallel with the same management and number of animals, differences between rooms and phases could be attributed to the application of the urease inhibitor. The results from the pre-test indicate that, in case of existing differences between rooms, these would result in higher emission mitigation. Therefore, the results from the case-control approach can be considered a conservative estimation of the mitigation potential.

The emission values of the control room averaged approximately 3 g h^{-1} LU^{-1}. This value corresponds to a particular situation (one farm, summer conditions) and can not be taken as representative of this production system. However, it is important to highlight that this value is consistent with emissions reported in the literature, which are typically between 2 and 3 g h^{-1} LU^{-1} (Hansen, Sørensen, & Lyngbye, 2007; Hayes, Curran, & Dodd, 2006; Koerkamp et al., 1998; Lynch, O'Shea, Sweeney, Callan, & O'Doherty, 2008; Saha, Zhang, Kai, & Bjerg, 2010). In fact, temperature and ventilation rate affect directly the emission rate (Ni, 1999), and therefore it is reasonable to expect that the emissions from the control room monitored in this study would be in the higher range of emission rates reported in literature. For example, the average ventilation in this study was more than 5 times higher than those reported by Seedorf et al. (1998a). Indoor temperature was also higher than those reported from the same dataset for fattening pigs on slatted floor in summer conditions (Seedorf et al. 1998b). This could suggest higher emission factors for ammonia under high-ventilated buildings under warm conditions. However, this hypothesis needs to be assessed with repeated measurements over the year and in more farms under similar conditions.

The application of the additive reduced ammonia emissions during the treatment phase. This study provides two

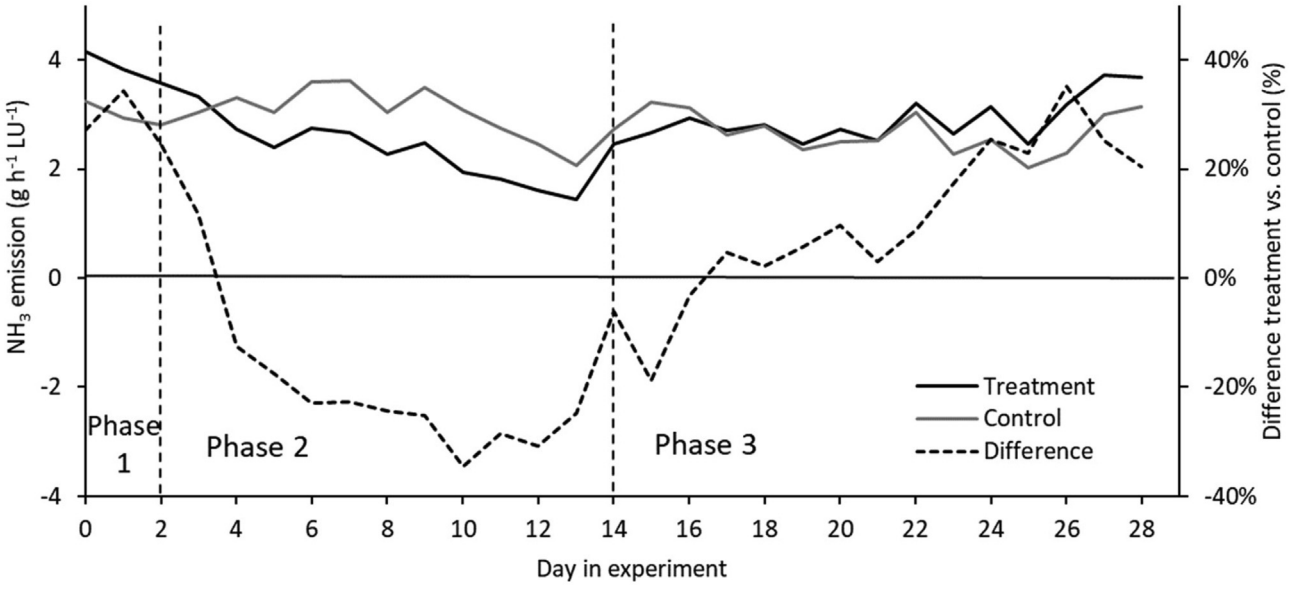

Fig. 5 – Evolution of ammonia emissions in the treatment and control rooms, as well as the relative difference among them (treatment-control). The three phases in the study are indicated: In Phase 1 no treatment was applied to any room, in Phase 2 the urease inhibitor was applied to treatment room, and in Phase 3 no treatment was applied to any room after Phase 2 had finished.

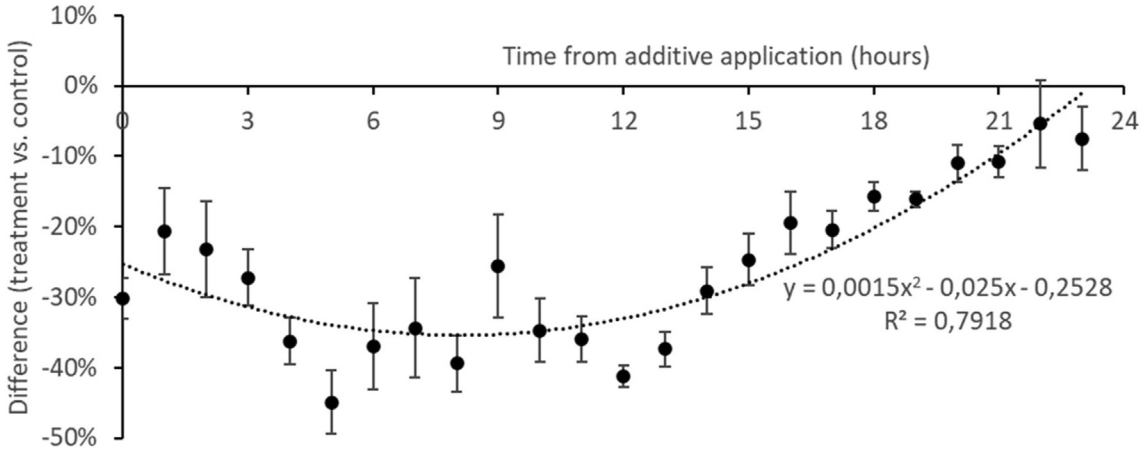

Fig. 6 – Difference between control and treatment rooms as a function of time (first 24 h) after application. The polynomic regression of this tendency is also shown.

quantitative estimations of this effect. The first estimation is obtained considering the in-time evaluation. This means that the same treatment room can be used as a control if the previous days of application (pre-treatment phase) are considered as a baseline. The post-treatment period was not used because the additive application could have an unpredictable effect after application stopped, for example due to inhibitor partial effect or to urea accumulation. This in-time approach provided a value of 43% reduction. The second estimation is the case-control approach using the control room as baseline. Using this approach, a 29% reduction was obtained.

The discrepancy between in-time and case-control estimations may arise from limitations in their calculation, particularly in the in-time approach. The in-time approach assumes that conditions in pre-treatment and treatment phases are similar. This is not possible because manure was accumulated in the pits underneath the slats, and therefore changes in the emission patterns could be expected. Furthermore, only two days were available in the pre-treatment phase until the urease inhibitor was applied. This may cause obtaining non-representative information from the pre-treatment phase, for example due to different environmental conditions or behaviour of animals during their first hours in the rooms. Apart from that, natural ventilation estimations are subjected to a wide range of uncertainty sources (Calvet et al., 2013) and therefore, absolute emission values provided here must be considered cautiously. However, using two identical rooms at the same time, with the same number of animals and management, could allow reducing calculation biases and do the evaluation in comparative

terms. Even though, two rooms with same dimensions and management could also differ in practice. Despite these limitations, the comparison of pre-treatment and post-treatment phases shows higher emissions in the treatment room than in the control room, and therefore differences in the treatment phase can be attributed to the urease inhibitor. For these reasons, it can be assumed that a 29% emission reduction can be achieved using a urease inhibitor in a daily application in fully-slatted pig farms in summer conditions.

This study used sensors with precision which was relatively near the measured differences (50 ppm CO_2, 1.5 ppm NH_3). As repeated measurements were conducted every hour ($n = 30$), the potential variability in concentrations and lack of precision was not identified as a relevant issue for the results provided in this study, and very consistent results (absolute values and variation patterns) were found throughout the study.

The emission reduction found in this study is in accordance with previous research conducted in dairy cattle farms. A strong reduction in urease activity was found after on-farm application of a urease inhibitor based on phosphorodiamidate (Hagenkamp-Korth et al., 2015). The effect of these additives to reduce ammonia emissions from dairy farms was recently confirmed by on-farm measurements. In dairy houses with solid floor and natural ventilation, a 40% reduction was found in summer conditions (Bobrowski, Willink, et al., 2021). For mechanically ventilated dairy farms with slatted floor, the additive was less effective since they found reductions from 17 to 23% (Bobrowski, van Dooren et al., 2021). It seems that application form on slatted floor (either to the slatted floor, or to the pit, or both) may play an essential role in determining the mitigation potential of this additive. Both studies reported the complexity of assessing emissions in dairy farms due to diversity of emitting surfaces and the interaction of the milking routine. These difficulties were not found for growing pigs in our study, where routine is simpler and surfaces more homogeneous. Results are also not comparable because the additive was applied on top of the floor in those studies, while in this study the additive was applied directly to the manure pit. For beef cattle, the use of a urease inhibitor increased N content in manure by 9–20%, although no difference in emissions could be tested due to emission variability (Parker et al., 2016). In our study, slurry composition could not be monitored and therefore we can not provide these figures.

The available literature supports the daily application of the inhibitor as used in this study. Recent research shows that highest reductions arise from 8 to 16 h after application (Bobrowski, Derno, et al., 2021; Bobrowski, van Dooren et al., 2021; Bobrowski, Willink, et al., 2021). Our results (Fig. 6) confirm this hypothesis, thus supporting the recommendation of daily applications. Considering this effect, the time of application could affect the mitigation potential since temperature and emissions vary during the day. According to our results, it seems that applications in the early morning would be more convenient as emissions tend to be higher during the daytime, but this effect could be confounded by changes in temperature and ventilation rates. Therefore, understanding these interactions and providing accurate recommendations needs further research.

As shown in Fig. 5, when the additive application finished emissions from the treated room did not rise abruptly but recovered gradually until they exceeded emissions from the control room three days after inhibitor application finished. Understanding post-treatment emission patterns is also necessary to establish proper abatement strategies. A rebound effect on emissions could be expected since abated emissions would result in a slurry more concentrate in urea. Once the effect of the additive stopped, urea conversion into ammonia is expected to increase, which would involve higher emissions at further stages. This effect was not clearly shown in the results of our post-treatment period, but it could be confounded because animals continued excretion, which would make both rooms behave more similarly. The potential rebound effect could be relevant if slurry is removed frequently from a house treated with urease inhibitor. In any case, it is necessary to evaluate the mitigation potential along the management chain.

The present study evaluated the ammonia reduction in a particular situation: one farm in summer conditions, continuous application for 12 days and no slurry removal from the pits. However, it is known that additive performance may be affected by particular circumstances on farm such as management of animals and manure, ambient conditions or additive use (McCrory & Hobbs, 2001). Therefore, further studies are needed to evaluate the effect of a urease inhibitor in a wider range of farms and conditions and validate the ammonia abatement found in this study.

Ammonia abatement in naturally ventilated pig farms is challenging. End of pipe techniques are effective but can not be applied to this type of buildings. Some building design strategies may also be effective, for example reducing the slatted floor area or using low emission slats (Philippe, Cabaraux, & Nicks, 2011). However, they involve a relevant investment by the farmer. When properly used, urease inhibitors may be considered as an interesting alternative to contribute abating ammonia emissions in the slurry management chain, as required by the new regulations across Europe.

5. Conclusions

This study evaluated the effect of applying a urease inhibitor in during part of the growing period in a naturally ventilated pig farm in summer conditions. The daily application of a urease inhibitor reduced emissions by 29% during the period that application was done. This study confirms the time-dependency of ammonia abatement and found that highest mitigation was found within 4–14 h after treatment. After application finished, emissions increased gradually and became similar to the untreated farm. Further studies are needed to evaluate additive performance in other environmental and farm conditions.

Declaration of competing interest

The co-authors Begoña Arrufat, Ignasi Salaet, Sergio Atares and Joaquin Romero are employees of Fertinagro Biotech, the company that supplied the additive

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