Mitigation of ammonia emissions from pig production using reduced dietary crude protein with amino acid supplementation

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Abstract

To mitigate ammonia (NH₃) emissions from pig production and understand the dynamic emission profiles, reduced dietary crude protein (CP) with amino acid supplementation was studied with 720 pigs in a 12-room research building for 155 days that covered from weaned to finishing stages. The pigs were divided into three 4-room groups and fed with 2.1%–3.8% reduced CP (T₁), 4.4–7.8% reduced CP (T₂), and standard (control) diets, respectively. Compared with the control group, T₁ and T₂ decreased manure volumes and manure NH₄⁺-N contents. Group-mean NH₃ emission from the control group was 68.9 g d⁻¹ AU⁻¹ (AU = 500 kg live mass). Emissions from T₁ (46.7 g d⁻¹ AU⁻¹) and T₂ (29.8 g d⁻¹ AU⁻¹) were reduced by 32.2% and 56.7% ($p < 0.05$), respectively. Dynamic peak NH₃ emissions appeared during the third nursery phase for T₁ and T₂, but delayed to the first grower phase for the control group.

Keywords: Air quality; air pollution abatement; animal feeding operation; dietary manipulation; pig production; pollution control.

1. Introduction

Ammonia (NH₃) emission from animal feeding operation has received increasing attention from the scientific world and regulatory agencies for its potential negative impacts on the environment, ecosystem, and human and animal health. The farms, which house more than a designated number of animals, or of which the emitted NH₃ exceed a reportable quantity, are subject to reporting and permitting requirements under the Emergency Planning and Community Right to Know Act (EPCRA) and the Comprehensive

Environmental Response, Compensation, and Liability Act (CERCLA) in the United States (EPA, 2009).

Ammonia emitted from animal production originates from either hydrolysis of urea in the urine, or decomposition of nitrogen (N) containing organics in the feces (Aarnink et al., 1995). About 70% of the N in the diet could be excreted in urine and feces, a potential N source of eutrophication in water body if not managed appropriately, and 31% N in the urine and feces could be lost as NH_3 emissions during house storage and land application (Aarnink and Verstegen, 2007). Increasing the utilization efficiency of dietary N and decreasing N in the excreta is a potential method to reduce NH_3 emissions. Therefore, feeding pigs with balanced nutrients has been considered effective in reducing NH_3 emissions due to reduced surplus nutrients in the excreta.

Crude protein, composed of amino acids (AA), is the primary source of N in pigs feed. Pigs do not require CP in the feed but their nutritional requirements varied substantially to different AA (Holden and Ensminger, 2006). Among the 10 essential AA that cannot be generated through internal metabolisms of pigs, the most limiting essential AA is Lysine, followed by Tryptophan and Threonine (Holden and Ensminger, 2006). The standard diet of pigs is formulated to meet the demand of Lysine, resulting in excessive intake of other AA by the pigs. If the amount of CP in the diet is reduced by using synthetic AA, there will be significantly less N excreted by the pigs (Radcliffe et al., 2005). Some studies have been conducted to investigate the effects of feeding pigs with CP-reduced diet on NH_3 emission from pig production. Portejoie et al. (2004) found that a decrease in dietary CP from 20% to 12% led to a decrease in NH_3 emissions by 63%. It was summarized from the previous studies that every 10 g kg^{-1} reduction in CP could lead to 10%–12.5% lower NH_3 emissions (Aarnink and Verstegen, 2007).

The reduction of CP does not necessarily result in inhibited pig growth if commercially available synthetic AA is supplemented with the ratio matching the growth demand of pigs. Reducing CP with sufficient AA supplementation in pig diet showed little impacts on the pig weight gains, despite reduced N retention (Portejoie et al., 2004; Toledo et al., 2014; Zervas and Zijlstra, 2002). Philippe et al. (2006) and Le et al. (2007) reported that supplying sufficient essential AA to the CP-reduced pig diet significantly restrained the NH_3 emissions while maintaining the normal performance of pigs.

Nevertheless, supplying synthetic AA excessively was reported to decrease the feed intake and weight gain of pigs (Edmonds and Baker, 1987).

However, previous studies could not fully reveal the effects of CP reduction on NH_3 emissions during different pig growth stages from weaned to finishing. Most of the field studies were of short-term experiments without covering the sufficiently long growth cycle of pigs. For example, NH_3 was observed for only 21 days in a 9-week field monitoring at a swine barn by Canh et al. (1998b). The study of Portejoie et al. (2004) was based on 15 pigs and a 30-day observation. Other studies were carried out with small number of pigs in experimental chambers (e.g., Power et al. 2007; Panetta et al. 2005a), where though the test environment was better controlled, the representativeness could be limited compared with field environment because of the scale effect and the substantial environment differences between in a chamber and a pig production building.

Lack of reliable data and continuous monitoring was another obstacle in the path of revealing the characteristics of NH_3 emissions from production of pigs under dietary manipulation. Some researchers (e.g., Hayes et al., 2004; Otto et al., 2003; Portejoie et al., 2004) determined NH_3 emissions by discretely quantifying NH_3 concentrations with limited number of samples using measurement techniques such as wet chemistry and gas detector tubes, which have relatively low sensitivity and low accuracy compared with high-end NH_3 analyzers (Ni and Heber, 2008). Because NH_3 in animal buildings exhibits profound diel variations (Saha et al., 2014; Ye et al., 2009), a limited number of concentration samples in a day could lead to significant bias in emission calculations.

So far, the dynamic profiles of NH_3 emissions from all pig growth stages affected by dietary manipulation are yet to be investigated. Moreover, experiments in controlled environment but closer to the field conditions are needed. The objective of this paper was to uncover the effects of reduced dietary CP with AA supplementation on NH_3 emissions from a swine environmental research building with 720 pigs, covering nursery to finishing stages.

2. Materials and Methods

2.1. Building description

The swine building is located at the Animal Sciences Research and Education Center, Purdue University, West Lafayette, Indiana. There are 12 rooms in total with six rooms along the south wall and other six along the north wall of the building. Each room measures $11.0\text{ m} \times 6.1\text{ m} \times 2.7\text{ m}$ ($L \times W \times H$) and is comprised of a pig living space (PLS) above a fully-slatted concrete floor and two under-floor isolated 1.8-m deep manure pits (Figure 1). There are 6 or 12 pens in each PLS that can house 60 finishing pigs.

[Insert Figure 1 here]

Two curtain-covered inlets above the east and west doors of the building allow fresh outdoor air enter into the building. The curtain above the east wall is controlled by a static pressure controller (Model SP-2, Airstream Ventilation Systems, Assumption, IL, USA). The other curtain above the west wall is controlled manually. The extent of the curtain opening is regulated, depending on the outdoor weather condition and the ventilation needs of the rooms.

The outdoor fresh air enters each room through three baffled V-shaped ceiling inlets and a perforated 38-cm diameter PVC air pipe installed 20 cm below the ceiling and along the room. Room air is exhausted via four direct-driven ventilation fans in each room: two variable-speed pit fans and two single-speed wall fans. The inlets of the 25-cm diameter pit fans (Model P4E30, Multifan, Bloomington, IL, USA) are connected to two 25.4-cm diameter perforated PVC exhaust air pipe in the pit. The two wall fans are installed side by side on the end wall: one is of 36-cm diameter (Model V4E35, Multifan), and the other is of 51-cm diameter (Model V4E50, Multifan). The measurement and calibration methods for both pit fans and wall fans were described by Ni et al. (2015).

Ventilation in each room is controlled independently with a Fancom controller (Model FCTC, Vancom BV, Panningen, The Netherlands). A propane heater (Model 379K, L.B. White Co. Onalaska, WI, USA) is installed in each room to provide supplementary heat when the room temperature is too low for pigs in winter. Two other propane heaters (Model Guardian 60, L.B. White Co. Onalaska, WI, USA)

are installed close to the east and west doors of the building to pre-heat the fresh air before it reaches the rooms in cold seasons.

2.2. Experiment description

Weaned piglets were moved into R1–R6 on Feb. 25, 2015, and into R7–R12 one week later on Mar. 4, 2015 (Table 1). There were 60 piglets in each room, weighed between 4.5 and 13.0 kg each at the beginning of the experiment. Pigs were fed based on their growth demand during the three production stages: nursery (from weaned to 25 kg), grower (25–70 kg), and finisher (70 kg to market). The duration of the nursery and grower stages lasted for 43 d and 63 d, respectively. The duration of the finisher stage lasted for 34 d in R4–R6 and R10–R12; and 41 d in R1–R3 and R7–R9.

[Insert Table 1 here]

The pig diet was based on yellow dent corn (7.5% CP), soybean meal (47.5% CP), corn DDGS (Distillers Dried Grains with Solubles, 7%, 30.9% CP), limestone, mono-calcium phosphate, salt, choice white grease, trace mineral premix, vitamin premix, phytase, Se premix, and Lincomix. The diet was also supplemented with essential AA, including L-lysine HCl, L-threonine, L-tryptophan, DL-methionine, L-valine, and L-isoleucine. The ingredients of pig diet, including the type and quantity of supplementary AA, changed upon pig dietary demands at different growth stages (Table 2). The percentage of the soybean meal increased throughout the four phases of the nursery stage and decreased until the last finisher phase, when it profoundly increased. That of the corns increased throughout the experiment until the last finisher phase, when it decreased slightly.

[Insert Table 2 here]

There were three groups of pigs in the 12 rooms based on the amount of CP in the feed: Control, Treated 1 (T_1), and Treated 2 (T_2). Each group had four replicated rooms: control group included R1, R4, R8, and R11; T_1 group included R2, R5, R9 and R10; T_2 group included R3, R6, R7 and R12 (Table 1). The control group was fed with standard diet. The two treated groups, T_1 and T_2 , were supplied with 2.1–3.8% and 4.4–7.8% CP reduced diet, respectively. To ensure sufficient essential AA in the diet, synthetic

AA was supplied increasingly from control to the T₂ group (Table 2).

2.3. Pig and manure

The pigs were weighed individually at both the beginning and the end of the experiment, as well as at the end of each growth stage. Pig numbers in each room were also recorded whenever there were reductions.

Weekly increments of manure volumes in the under-floor pits were calculated by multiplying the manure pit area (67.08 m² for the two pits in each room) by the differences of manure depths, which were obtained by subtracting the manure headspace heights from the pit depth. The manure headspace heights were measured weekly using a Laser Distance Meter (Model Leica Disto Special-5, Leica Geosystems Inc., Norcross, GA). Accumulated volumes of manure production was the summations of the weekly manure increments in the same room.

Four vacuum manure column samples were taken in each room in three growth stages. Those from the same room were pooled and mixed for analyzing concentrations of ammonium nitrogen (NH₄⁺-N) and other variables (included dry matter, ash, phosphorus, and total nitrogen), which will be reported elsewhere. Manure NH₄⁺-N concentrations were measured using the Kjeldahl procedure (Nelson and Sommers, 1972).

2.4. Air quality monitoring

The swine building was equipped with a comprehensive air quality online monitoring system, which included analyzers for gas concentration measurement, and sensors for fan operation and airflow rate monitoring, and indoor environment monitoring.

2.4.1. Air sampling and gas concentration measurement

There was a total of 25 air sampling locations (ASLs) in the building. One of the ASLs was installed in the building hallway to sample room inlet air. The other 24 ASLs were distributed in the 12 rooms, two in each room: one at 120 cm from the inlet of the 36-cm wall fan to sample exhausting room air and the other inside the inlet pipe of the pit fans to sample exhausting manure headspace air. Air samples were collected for 20 min at the inlet ASL and 10 min at other ASLs, switching from one to the other. From

February 25 to April 18, air samples were switched among the 12 pit ASLs and the inlet air, because only pit fans were in use during this period. Starting from April 19 to July 30, when all the wall fans were turned on, air sampling at the 12 wall fans were activated.

Ammonia concentrations in the sampling air were measured continuously using an Innova photoacoustic infrared multi-gas monitor (Model 1412, LumaSense Technologies, Ballerup, Denmark). Certified zero air and span NH_3 gas (49.2 ppm) were used to check the precision of the gas analyzer weekly. The precision, expressed as relative standard deviation (RSD), was 4% throughout this experiment.

2.4.2. Ventilation monitoring

The operational status of each of the 24 wall fans was monitored. The AC voltage to each wall fan was converted to DC voltages and recorded. The static pressures between each room and its outside end wall where the wall fans were installed were measured using a differential pressure transducer (M260, Setra System, Boxborough, MA). A linear model (ventilation rate vs. static pressure) was established for each wall fan during two fan calibration sessions before and after the experiment. A detailed description of this method was published by Ni et al. (2015).

Ventilation rates of the pit fans were measured directly using an innovative Pit Exhaust Airflow Measurement Assembly (PEAMA), of which the output unit was in air volume per unit of time. The PEAMA was composed of a PVC pipe (914-mm long, 300-mm ID, and 305-mm OD), a 610-mm long flow straightener, and an anemometer (Ni et al., 2016). The anemometers (Model 27106RS, R. M. Young, Traverse City, MI, USA) were calibrated in the lab before and after the experiment.

2.4.3. Other measurements

Air temperatures at all ASLs were measured with T-type thermocouples. The air temperature data were used to convert volumetric NH_3 concentration in ppm to mass concentration in mg m^{-3} for emission calculation. Relative humidity (RH) transmitters (Model HX92BC, Omega, Atlanta, GA, USA) were installed in selected rooms (R1, R2, R3, and R11). Passive Infrared Detector (PID) motion sensors (Model SRN-2000 Detector, Visonic Inc., Bloomfield, CT, USA) were installed on the end wall of each

room, 2.2 m above the floor and tilted downward at 15°, to monitor the pig activities. The RH and activity data were used for experiment quality control.

2.4.4. Data acquisition, signal processing, and air sampling control

The multi-gas monitor and all online sensors were connected to an on-site computer system (OSCS) for data acquisition and signal processing. The OSCS consisted of a PC, data acquisition hardware, and custom-developed software AirDAC (Ni and Heber, 2010). Analog or digital output signals from the monitor and sensors were acquired at 1 Hz, converted to data in engineering units, then averaged over 15-sec and 1-min intervals and saved in two separate AirDAC data files. At 2:00 AM each day, measurement data from the previous day were automatically pre-processed to generate data statistics and graphs in an Excel file that was delivered to researchers via an automatic email. The OSCS also automatically controlled air sampling locations, time duration at each location, and sequence of different locations.

2.4.5. Data processing

Collected raw data were processed using custom software CAPECAB (Fibre Recovery Systems, Inc., Calgary, AB, Canada). After data were imported into CAPECAB, they went through a validation process. Raw data were plotted and subject to visual inspection. Invalid data due to the sensor and other errors were removed after being confirmed with the experiment field note. Validated data were corrected when necessary based on instrument and sensor calibrations. Data of manure volume, pig number, pig weight, and NH₃ concentration at individual locations were interpolated in the CAPECAB, to match the other measurement, including ventilation and environmental variables.

Because NH₃ concentrations at multiple locations were measured using the location-shared gas monitor, there was a transition time when switching from one location to another. During data processing, only the last 3 min of NH₃ concentration data during the 10- and 20-min sampling time were extracted and used. Data during the 7 and 17 min transition time at the beginning of line switching was excluded.

Ventilation rates of the 24 pit fans were calculated real-time in the OSCS. Ventilation rates of the 24 wall fans were calculated during post-measurement data processing using the fan operation time and fan models, in which the ventilation rate was a function of the measured static pressure across the end wall

and the fan power supply voltage. The models were developed during on-site wall fan testing (Ni et al. 2015).

The unit of measured NH₃ concentrations in ppm was converted to mg m⁻³ using the ideal gas law before NH₃ emission rate calculation. Ammonia emission rate for each room at a given minute was calculated with Eq. (1).

$$E_i = (C_{i,p} - C_{inlet}) \times V_{i,p} + (C_{i,w} - C_{inlet}) \times V_{i,w} \quad (1)$$

where E_i is NH₃ emission rate from i^{th} room, mg min⁻¹; $C_{i,p}$ and $C_{i,w}$ are NH₃ concentrations at the pit fan exhaust and wall fan exhaust, respectively, of the i^{th} room, mg m⁻³; C_{inlet} is NH₃ concentration at the room inlet, mg m⁻³; $V_{i,p}$ and $V_{i,w}$ are ventilation rates of the two pit fans and two wall fans, respectively, in i^{th} room, m³ min⁻¹.

The 1-min data of NH₃ emission rates were used to obtain sample means and daily means. The phase, stage, and cycle means were calculated by averaging the daily means over the phase, stage or cycle, respectively, for individual rooms, test group of 4 rooms, and entire building of 12 rooms (Table 3). Standard deviations and statistic tests were also calculated on daily means with relevant room coverage. The ANOVA (analysis of variance) analysis was applied to test the effects of dietary treatment on the NH₃ emissions by using the **proc anova** in the software SAS 9.4 (SAS Institute Inc., Cary, NC).

[Insert Table 3]

3. Results

3.1. Room environmental condition

3.1.1. Temperature

The phase mean outdoor temperature increased throughout the experiment (Figure 2, bottom). From N1 to G1 periods, the phase mean outdoor temperature increased from -7.4 °C to 11.7 °C, and the propane heaters in the rooms were in use to maintain optimal temperatures and supply sufficient heat for the growth piglets. Complete shut-off of the heaters began from phase G2 when the phase mean outdoor temperature reached 19.3 °C. It continued to increased and reached 24.3 °C by the phase F2.

From phase N1 to N4, the building phase mean temperature increased from 22.8 to 23.9 °C in the pits but decreased from 33.2 to 25.2 °C in the PLS. The temperatures measured in the PLS were higher than those in the pit during the nursery period when the heaters were in use in all rooms. During the grower and finisher stages, the building phase mean temperatures in the pits and the PLS were close to each other, and both increased towards the end of the cycle. From phase G1 to F2, the building phase mean temperatures increased from 22.1 °C to 26.0 °C in the pits and from 23.5 °C to 25.5 °C in the PLS.

Throughout the experiment, the group cycle means of pit temperatures were the same for the T₁ and T₂ groups (both 23.8 ± 2.0 °C), but slightly lower than that in the control group (24.1 ± 2.1 °C). There were no significant differences in the group cycle means of the PLS temperatures ($p > 0.05$).

[Insert Figure 2 here]

3.1.2. Ventilation

The pit fans were kept on throughout the experiment. The building phase mean pit fan ventilation rates averaged at 24.9 and 27.4 m³ min⁻¹ for the first two phases N1 and N2, and increased to 41.9 m³ min⁻¹ by the end of the nursery stage (Figure 3, top). It was an essential measure to provide minimum ventilation rate during very cold days, preventing the substantial decrease of room temperature and removing extra airborne pollutants and moisture from the room. The pit ventilation rate maintained maximum performance during the grower and finisher stages, ranging from 41.9 to 49.7 m³ min⁻¹. The group phase mean of pit ventilation rate for the control group was higher than that for the two treated groups from phase N1 to G1, but they were of the same level for the rest of the time.

The wall fans were kept off during the nursery stage. They were off for most of the time but turned on occasionally during phases G1 and G2, providing building phase mean ventilation rates of 9.8 ± 19.8 and 73.2 ± 43.8 m³ min⁻¹, respectively. The wall fans were in full performance since G3 when the sensible heat was accumulated rapidly in the rooms, and timely removal of the heat was required to keep a moderate indoor environment. The building phase mean ventilation rate reached 114.0 m³ min⁻¹ by phase G3, and maintained maximum performance during the finisher stage. It was 125.1 and 126.5 m³ min⁻¹, respectively, during F1 and F2.

The group cycle mean of total ventilation rates of the control, T₁, and T₂ groups were 109.5 ± 62.7 , 110.9 ± 64.8 , $109.4 \pm 65.9 \text{ m}^3 \text{ min}^{-1}$, respectively. From phase N1 to G1, the group phase mean of the total ventilation rate was higher for the control group than the other two groups due to the higher pit ventilation rates. From phase G2 to F2, the group phase mean ventilation rates of the three groups was not statistically different ($p > 0.05$).

3.1.3. Manure volume and NH_4^+ -N content

The accumulated manure volumes throughout the cycle were control $> \text{T}_1 > \text{T}_2$, though not significantly different ($p > 0.05$, Figure 3). They were 46.8, 43.7 and 41.0 m^3 for the control, T₁ and T₂ groups, respectively. This result was consistent with the findings of Portejoie et al. (2004) that the amount of pig slurry decreased as the CP supply was reduced.

[Insert Figure 3 here]

The NH_4^+ -N contents in manure were also the highest for the control group and the lowest for the T₂ group (Figure 4). The differences among the three groups were statistically significant during all three growth stages ($p < 0.05$). This result agreed with the study of Power et al. (2007) who showed a reduced NH_4^+ -N content of the manure from pigs fed with low CP diet. The reduced NH_4^+ -N in manure was primarily from the reduced urinary N (Canh et al., 1998; Kerr and Easter, 1995; Portejoie et al., 2004)

[Insert Figure 4 here]

3.2. Ammonia concentration

The building phase mean pit NH_3 concentrations averaged at 1.4 ± 0.3 ppm at the beginning (phase N1) and reached 4.9 ± 3.9 ppm by the end of the experiment (phase F2). Because the sampling of PLS NH_3 concentration at the start of wall fan use from phase G1, the building phase mean PLS NH_3 concentrations were quite constant throughout the experiment: they were 3.3 ± 1.6 ppm in phase G1, and maintained 3.3 ± 0.9 ppm in F2. Ammonia concentrations in the PLS were mostly between 50% and 70% of those in the pits (Table 4).

Though the NH_3 concentrations had been lower and very close in the treated groups during N2 and N3, they became statistically different from phase N4 ($p < 0.05$). The measured group phase mean NH_3

concentrations both in the pits and PLS followed the order of control > T₁ > T₂ ($p < 0.05$). The differences of NH₃ concentrations among the pits of the control group were much larger than those in the two treated groups. Because there were no significant differences among the group phase mean pit ventilation rates, higher temperature in the pit of R4 (24.8 °C) than the temperatures in other rooms (21.0–23.0 °C) could lead to the differences among the four control rooms. Higher pit air temperature positively affected the manure temperature, thus accelerated the bacterial ammonification in the manure (Elliott and Collins, 1982). It could also promote the gaseous NH₃ release from liquid manure by influencing the dissociation constant, which determined the amount of NH₃ molecular in the manure solution, and Henry's constant, which closely associated with the mass concentration of NH₃ at the gas-liquid interface (Ni, 1999).

[Insert Table 4 here]

3.3. Ammonia emission

3.3.1. Daily differences

The building cycle mean NH₃ emission was 48.5 g d⁻¹AU⁻¹. The highest and the lowest room cycle mean emission rates were 110.1 (R4) and 21.5 (R7) g d⁻¹AU⁻¹, respectively. The building daily mean emission rates during the experiment ranged from 3.7 to 186.2 g d⁻¹AU⁻¹.

In the control group, both R4 and R8 showed emission rates as high as 150 g d⁻¹AU⁻¹ between d 20 and d 30 (Figure 5). In R4, high emission rates (between 126.7 and 186.2 g d⁻¹AU⁻¹) lasted until d 65 and decreased afterward. In R8, it decreased as soon as the highest rate was reached on d 25. The highest emission rates for R1 and R11 were 66.9 and 82.1 g d⁻¹AU⁻¹, respectively, which were observed between d 35 and d 90. The differences in the daily emission rates were larger in the control group rooms than in the rooms of two treated groups.

[Insert Figure 5 here]

For the two treated groups, the highest room daily mean emission rates were observed between d 20 and d 30. In the T₁ group, the maximum daily emission rates were from 52.9 to 108.8 g d⁻¹AU⁻¹ for the four rooms; in the T₂ group, they ranged from 37.8 to 79.3 g d⁻¹AU⁻¹. At the later stage of the experiment, the room daily mean emission rates of the control rooms still varied substantially within the group, but

those from the two treated groups converged to similarly low levels (Figure 5).

3.3.2. Growth stage differences

During the nursery stage, the amount of NH_3 emitted from the control, T_1 and T_2 group accounted for 29.7%, 30.8%, and 36.9%, respectively, of that emitted throughout the respective experimental cycle. During the grower stage, the ratios were 49.2%, 48.8%, and 42.5%, respectively. They were 21.1%, 20.4%, and 20.6%, respectively, during the finisher stage. It was consistent in all three groups that nearly half of the emissions were emitted during the grower stage. However, the T_2 group emitted more NH_3 than the other two groups during the nursery stage.

[Insert Table 5 here]

The highest group phase mean emission rate was observed at different growth stage for the three groups: It was in the phase G1 ($99.6 \text{ g d}^{-1} \text{ AU}^{-1}$) for the control group, and in the phase N3 for the two treated groups. From the phase N3, the group phase mean emissions from T_2 were only 34%–45% of those from the control group.

4. Discussion

4.1. Effect of dietary CP reduction with AA supplementation on cycle mean NH_3 emissions

The total NH_3 emitted throughout the experiment were 37.3 kg, 25.0 kg, and 16.0 kg from the control, the T_1 , and T_2 group, respectively. The NH_3 emitted from T_1 , and T_2 groups were about 67.0% and 42.9% of that from the control group.

The group cycle mean emission from the control group was the highest among all the three groups. It averaged at $68.9 \text{ g d}^{-1} \text{ AU}^{-1}$, with the daily mean ranged from 4.6 to $186.2 \text{ g d}^{-1} \text{ AU}^{-1}$. Large differences among the rooms were found within the control group, with the standard deviation of $40.0 \text{ g d}^{-1} \text{ AU}^{-1}$. The average emission rates were lower for the T_1 and T_2 groups, which were 46.7 ± 19.5 and $29.8 \pm 10.6 \text{ g d}^{-1} \text{ AU}^{-1}$, respectively.

A number of dietary factors could account for the discrepancies among groups. On the one hand, the standard diet fed to the pigs of the control group was formulated to meeting the requirement of lysine, the most limiting AA for pig growth, resulting in excessive non-limiting AA. The excessive non-limiting AA

could be mostly catabolized and excreted from the pigs in the form of urea (Brown and Cline, 1973; Toledo et al., 2014). Zervas et al. (2002) reported that the daily urinary N excretion was linearly correlated with plasma urea. Otherwise, in the two treated groups, according to Panetta (2005b), reduced dietary CP might lead to reduced mass and changed chemical forms of excreted N, as well as the altered ratio of urinary N to fecal N.

On the other hand, the supplemented crystalline AA was more bioavailable than the AA bounded in the feed ingredients (Figueroa et al., 2002; Toledo et al., 2014). Higher utilization efficiency and less excretion of the supplemented AA could lead to lower NH_3 emissions from the T_1 and T_2 groups.

Also, the CP-reduced diet of the treated groups T_1 and T_2 were compensated with increased corns, which were a rich source of carbohydrates and supposed to be nearly 100% digested in the intestine (Otto et al., 2003; Smith et al., 2004). When the intestinal microflora had access to more carbohydrates as fermentation substrate, vigorous microbial synthesis could occur, resulting in increased microbial utilization of dietary N and excreted N in the feces. In addition, decreased dietary CP could lead to reduced urinary pH by promoting the VFA production (Canh et al., 1998a; Otto et al., 2003; Portejoie et al., 2004), and alleviated potential NH_3 release.

4.2. Effect of dietary CP reduction with AA supplementation on phase mean NH_3 emissions

The NH_3 emissions from the T_1 and T_2 group were lower than that from the control group, and this effect became statistically significant from the phase N3 ($p < 0.05$, Table 5).

During the nursery phases N1–N3, the CP was reduced by 2.1%–2.5% for the T_1 and by 4.4–5.0% for the T_2 groups; while the AA was supplied with the approximate ratio 1:3:7 (control: T_1 : T_2 , Table 2). A total of 1.3 and 2.4 kg NH_3 emission was reduced for the T_1 and T_2 groups, respectively, compared with that emitted from the control group (Table 6). In the phase N4, the reduced CP was 3.7% and 7.6%, respectively, for the T_1 and T_2 groups, and the amino acids were supplied only to the T_1 and T_2 groups, with the ratio of 0.3% and 1.0%, respectively. Throughout phase N4, the emitted NH_3 from the T_1 and T_2 groups was 2.0 and 2.8 kg more, respectively, than that from the control group. The overall reduction of NH_3 during the nursery stage was 3.3 kg for the T_1 and 5.1 kg for the T_2 groups, compared with the

control group.

[Insert Table 6 here]

During the grower stage, the percentages of the reduced dietary CP were 3.7% in the T₁ and 7.8 % in the T₂ groups, and the AA was supplied to the two treated groups only (0.3% to T₁ and 1.0% to T₂, Table 2). The emitted NH₃ from the control group decreased substantially, from 7.2 kg in G1 to 5.0 kg in G3; but that from the two treated groups were quite constant, about 4.1 kg per phase from the T₁ group and 2.2 kg per phase from the T₂ group (Table 6). The total amount of NH₃ emitted from the control, T₁ and T₂ groups were 18.4, 12.2 and 6.8 kg, respectively, during the grower stage.

During the finisher stage, the emitted NH₃ was 7.9, 5.1 and 3.3 kg from the control, T₁, and T₂ group, respectively. A total of 2.8 and 4.6 kg NH₃ was reduced for the T₁ and T₂ group, compared with the control.

4.3. Non-dietary influencing factors

Ammonia emission from a confined pig building was mainly influenced by the building ventilation rate and the NH₃ release rate at manure surface. The release rate of NH₃ was primarily affected by the TAN (total ammoniacal nitrogen) concentration in manure, the mass transfer coefficient, which was dependent on temperature, the air velocity over the manure emitting surface, and the area of emitting surface (Monteny and Erisman, 1998; Philippe et al., 2011).

Though not significantly different, the group cycle mean pit temperature and pit ventilation rate were also the highest for the control group and the lowest for the T₂ group. This could contribute to the higher emission rates of the control group and lower of the T₂ group.

Pig weights did not demonstrate as a direct influence factor on NH₃ emissions in this study. The treatments had little impacts on the group phase mean pig weight and weight gains ($p > 0.05$). In the meanwhile, the temperature and ventilation rate were not likely to be influenced by the heat production of pigs. The total heat production from finishing pigs at 20 °C was related to the pig weight and the surrounding temperature (CIGR, 2002). In this study, the group phase mean pig weight and room temperature were not significantly different among groups. Therefore, the heat produced by the three

groups was not expected to cause substantial differences among the groups.

Different levels of manure NH_4^+ -N were observed among the three groups ($p < 0.05$): the highest for the control group, and the lowest for the T_2 group. The manure NH_4^+ -N of the T_1 group corresponded to 16.9%, 20.8% and 15.3% less than that of the control group, respectively, excreted during the nursery, grower and finisher stages. Pigs in the T_2 group corresponded to an NH_4^+ -N reduction of 40.3%, 45.9% and 29.6%, respectively. The CP reduced diet in this study resulted in significantly less manure NH_4^+ -N contents in the two treated groups. This might have directly lead to less NH_3 emissions from the two treated groups.

5. Conclusions

The following conclusions were drawn:

1. Reduction of dietary CP decreased accumulated manure volumes and the manure NH_4^+ -N contents. The higher NH_4^+ -N concentrations, along with higher pit temperatures and ventilation rates, contributed to the higher NH_3 emissions from the control group.
2. The diet CP reduction with AA supplementation effectively mitigated NH_3 emissions. Compared with the control group, T_1 , and T_2 reduced NH_3 emissions by 32.2% and 56.7%, respectively.
3. The peak NH_3 emissions were observed in the nursery stage N3 for the two treated groups, but delayed for the control group in grower stage G1.

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References

1. Aarnink, A.J.A., Keen, A., Metz, J.H.M., Speelman, L., Verstegen, M.W.A., 1995. Ammonia emission patterns during the growing periods of pigs housed on partially slatted floors. J. Agric. Eng.

- Res. 62(2), 105–116. <http://dx.doi.org/10.1006/jaer.1995.1069>.
2. Aarnink, A.J.A., Verstegen, M.W.A., 2007. Nutrition, key factor to reduce environmental load from pig production. *Livest. Sci.* 109(1-3), 194–203. <http://dx.doi.org/10.1016/j.livsci.2007.01.112>.
  3. Aarnink, A.J.A., Wagemans, M.J.M., 1997. Ammonia volatilization and dust concentration as affected by ventilation systems in houses for fattening pigs. *Trans. ASAE.* 40(4), 1161–1170.
  4. Brown, J.A., Cline, T.R., 1974. Urea excretion in the pig : An indicator of protein quality and amino acid requirements. *J. Nutr.* 104(5), 542–545.
  5. Canh, T.T., Aarnink, A.J.A., Schutte, J.B., Sutton, A., Langhout, D.J., Verstegen, M.W.A., 1998a. Dietary protein affects nitrogen excretion and ammonia emission from slurry of growing-finishing pigs. *Livest. Prod. Sci.* 56(3), 181–191. [http://dx.doi.org/10.1016/S0301-6226\(98\)00156-0](http://dx.doi.org/10.1016/S0301-6226(98)00156-0).
  6. Canh, T.T., Aarnink, A.J., Verstegen, M.W., Schrama, J.W., 1998b. Influence of dietary factors on the pH and ammonia emission of slurry from growing-finishing pigs. *J. Anim. Sci.* 76(4), 1123–1130. <http://dx.doi.org/10.2527/1998.7641123x>.
  7. CIGR, 2002. Climatization of animal houses. Heat and moisture production at animal and house levels., CIGR 4th Report of Work Group on Climatization of animal houses. Horsens, Denmark.
  8. Edmonds, M.S., Baker, D.H., 1987. Amino acid excesses for young pigs: Effects of excess methionine, tryptophan, threonine or leucine. *J. Anim. Sci.* 64(6), 1664–1671. <http://dx.doi.org/10.2527/jas1987.6461664x>.
  9. Elliott, H.A., Collins, N.E., 1982. Factors affecting ammonia release in broiler houses. *Trans. ASAE.* 25(2), 413–418. <http://dx.doi.org/10.13031/2013.33545>.
  10. EPA, 2009. CERCLA/EPCRA Administrative Reporting Exemption for Air Releases of Hazardous Substances from Animal Waste at Farms. https://www.epa.gov/sites/production/files/2013-08/documents/cafo_rule_fact_sheet.pdf (accessed 6-2016).
  11. Figueroa, J.L., Lewis, A.J., Miller, P.S., Fischer, R.L., Gómez, R.S., Diedrichsen, R.M., 2002. Nitrogen metabolism and growth performance of gilts fed standard corn-soybean meal diets or low-

- crude protein, amino acid-supplemented diets. *J. Anim. Sci.* 80(11), 2911–2919.
<http://dx.doi.org/10.2527/2002.80112911x>.
12. Hayes, E.T., Leek, A.B.G., Curran, T.P., Dodd, V.A., Carton, O.T., Beattie, V.E., O'Doherty, J.V., 2004. The influence of diet crude protein level on odour and ammonia emissions from finishing pig houses. *Bioresour. Technol.* 91(3), 309–315. [http://dx.doi.org/10.1016/S0960-8524\(03\)00184-6](http://dx.doi.org/10.1016/S0960-8524(03)00184-6).
  13. Holden, P.J., Ensminger, M.E., 2006. *Swine science*, 7th ed. Pearson Education Ltd., New Jersey.
  14. Kerr, B.J., Easter, R.A., 1995. Effect of feeding reduced protein, amino acid-supplemented diets on nitrogen and energy balance in grower pigs. *J. Anim. Sci.* 73(10), 3000–3008.
<http://dx.doi.org/10.2527/1995.73103000x>.
  15. Le, P.D., Aarnink, A.J.A., Jongbloed, A.W., van der Peet Schwing, C.M.C., Ogink, N.W.M., Versiegen, M.W., 2007. Effects of crystalline amino acid supplementation to the diet on odor from pig manure. *J. Anim. Sci.* 85(3), 791–801. <http://dx.doi.org/10.2527/jas.2006-644>.
  16. Monteny, G.J., Erisman, J.W., 1998. Ammonia emission from dairy cow buildings: A review of measurement techniques, influencing factors. *Netherlands J. Agric. Sci.* 46(3), 225–247.
  17. Nelson, D.W., Sommers, L.E., 1972. A simple digestion procedure for estimation of total nitrogen in soils and sediments. *J. Environ. Qual.* 1(4), 423–425.
<http://dx.doi.org/10.2134/jeq1972.00472425000100040020x>.
  18. Ni, J.-Q., 1999. Mechanistic models of ammonia release from liquid manure: A review. *J. Agric. Eng. Res.* 72(1), 1–17. <http://dx.doi.org/10.1006/jaer.1998.0342>.
  19. Ni, J.-Q., Diehl, C.A., Liu, S., Lopes, I.M., Radcliffe, J.S., Richert, B., 2015. An innovative ventilation monitoring system at a pig experimental building. In: *International Symposium on Animal Environment and Welfare*. Beijing, China: China Agriculture Press. pp. 58-65.
  20. Ni, J.-Q., Heber, A.J., 2010. An on-site computer system for comprehensive agricultural air quality research. *Comput. Electron. Agric.* 71(1), 38–49. <http://dx.doi.org/10.1016/j.compag.2009.12.001>.
  21. Ni, J.-Q., Heber, A.J., 2008. Sampling and Measurement of Ammonia at Animal Facilities. *Adv. Agron.* 98, 201–269. [http://dx.doi.org/10.1016/S0065-2113\(08\)00204-6](http://dx.doi.org/10.1016/S0065-2113(08)00204-6).

22. Ni, J.-Q., Kaelin, D., Lopes, I.M., Liu, S., Diehl, C.A., Zong, C., 2016. Design and performance of a direct and continuous ventilation measurement system for variable-speed pit fans in a pig building. *Biosyst. Eng.* 147, 151–161. <http://dx.doi.org/10.1016/j.biosystemseng.2016.04.011>.
23. Otto, E.R., Yokoyama, M., Hengemuehle, S., von Bermuth, R.D., van Kempen, T., Trottier, N.L., 2003. Ammonia, volatile fatty acids, phenolics, and odor offensiveness in manure from growing pigs fed diets reduced in protein concentration. *J. Anim. Sci.* 81(7), 1754–1763. <http://dx.doi.org/10.2527/2003.8171754x>.
24. Panetta, D.M., Powers, W.J., Xin, H., Kerr, B.J., 2005a. Nitrogen excretion and ammonia emissions from pigs fed reduced crude protein diets or yucca extract. *Animal Industry Report: AS 651, ASL R2014*. http://lib.dr.iastate.edu/ans_air/vol651/iss1/49 (accessed 11-2016).
25. Panetta, D.M., Powers, W.J., Xin, H., Kerr, B.J., Stalder, K.J., 2005b. Nitrogen excretion and ammonia emissions from pigs fed modified diets. *J. Environ. Qual.* 35(4), 1297–1308. <http://dx.doi.org/10.2134/jeq2005.0411>.
26. Philippe, F.-X., Cabaraux, J.-F., Nicks, B., 2011. Ammonia emissions from pig houses: Influencing factors and mitigation techniques. *Agric. Ecosyst. Environ.* 141(3-4), 245–260. <http://dx.doi.org/10.1016/j.agee.2011.03.012>.
27. Philippe, F.-X., Laitat, M., Canart, B., Farnir, F., Massart, L., Vandenheede, M., Nicks, B., 2006. Effects of a reduction of diet crude protein content on gaseous emissions from deep-litter pens for fattening pigs. *Anim. Res.* 55(5), 397–407. <http://dx.doi.org/10.1051/animres:2006029>.
28. Portejoie, S., Dourmad, J.Y., Martinez, J., Lebreton, Y., 2004. Effect of lowering dietary crude protein on nitrogen excretion, manure composition and ammonia emission from fattening pigs. *Livest. Prod. Sci.* 91(1-2), 45–55. <http://dx.doi.org/10.1016/j.livprodsci.2004.06.013>.
29. Powers, W.J., Zamzow, S.B., Kerr, B.J., 2007. Reduced crude protein effects on aerial emissions from swine. *Appl. Eng. Agric.* 23(4), 539–546. <http://dx.doi.org/10.13031/2013.23487>.
30. Radcliffe, S., Richert, B., Sholly, D., Foster, K., Hollas, B., Lim, T., Ni, J., Heber, A., Sutton, A., 2005. Diet Modification to Reduce Odors, Gas Emissions and Nutrient Excretions from Swine

- Operations. In: *Mitigating Air Emissions from Animal Feeding Operations*. Des Moines, Iowa, May 19-20, eds, E. Muhlbauer et al. pp. 114-119.
31. Saha, C.K., Ammon, C., Berg, W., Fiedler, M., Loebstin, C., Sanftleben, P., Brunsch, R., Amon, T., 2014. Seasonal and diel variations of ammonia and methane emissions from a naturally ventilated dairy building and the associated factors influencing emissions. *Sci. Total Environ.* 468–469, 53–62. <http://dx.doi.org/10.1016/j.scitotenv.2013.08.015>.
  32. Smith, L.F., Lemay, S.P., Patience, J.F., Zijlstra, R.T., 2004. Effects of dietary crude protein level and sugar beet pulp inclusion on nitrogen excretion patterns in grower and finisher pigs. *Can. J. Anim. Sci.* 84(4), 717–720. <http://dx.doi.org/10.4141/A04-015>.
  33. Toledo, J.B., Furlan, A.C., Pozza, P.C., Carraro, J., Moresco, G., Ferreira, S.L., Gallego, A.G., 2014. Reduction of the crude protein content of diets supplemented with essential amino acids for piglets weighing 15 to 30 kilograms. *Rev. Bras. Zootec.* 43(6), 301–309. <http://dx.doi.org/10.1590/S1516-35982014000600004>.

Figure captions

Figure 1. East-side view of the swine experimental research building. PLS = pig living space.

Figure 2. Building phase means and standard deviations of temperatures (top) and ventilation rates (bottom) during the entire pig cycle. PLS = pig living space.

Figure 3. Building phase means and standard deviations of pit manure volumes for the three groups.

Figure 4. Manure $\text{NH}_4^+\text{-N}$ contents for the three groups during three growth stages.

Figure 5. Comparison of daily mean ammonia emission rates from the control (top), T1 (middle), and T2 (bottom).

Table 1. Overview of the experimental design, and start- and end-of-experiment pigs.

Design and pigs	Room											
	1	2	3	4	5	6	7	8	9	10	11	12
Experiment design ^a	Ctrl	T ₁	T ₂	Ctrl	T ₁	T ₂	T ₂	Ctrl	T ₁	T ₁	Ctrl	T ₂
Start date ^b	2/25	2/25	2/25	2/25	2/25	2/25	3/4	3/4	3/4	3/4	3/4	3/4
Start pigs (n)	60	60	60	60	60	60	60	60	60	60	60	60
Start pig weight (kg)	5.4	5.4	5.4	7.2	7.1	7.1	5.4	5.5	5.4	6.9	6.9	6.9
End date ^b	7/23	7/23	7/23	7/16	7/16	7/16	7/30	7/30	7/30	7/23	7/23	7/23
Total days (d)	148	148	148	141	141	141	148	148	148	141	141	141
End pigs (n)	58	59	57	57	60	59	60	59	57	58	59	60
End pig weight (kg)	130.4	131.2	126.3	129.6	129.0	124.9	126.3	128.6	128.9	127.1	127.5	122.8

^a. Ctrl, T₁ and T₂ stand for the control group, treated 1 group, and treated 2 group, respectively.

^b. Month/date in 2015.

Table 2. Primary ingredients of the pig diet.

Stage	Feeding phase ^a	Date ^b		Days (n) ^c	Main diet ingredient: C/SBM/CP/AA (%) ^d		
		R1–R6	R7–R12		Control	Treated 1	Treated 2
Nursery	N1	2/25–3/5	3/4–3/12	8	28.0/15.0/25.0/0.1	31.5/15.0/22.9/0.3	35.2/15.0/20.6/0.7
	N2	3/5–3/12	3/12–3/19	7	34.1/18.0/23.8/0.1	37.9/18.0/21.6/0.3	41.8/18.0/19.1/0.7
	N3	3/12–3/26	3/19–4/2	14	39.5/20.0/31.2/0.1	43.6/20.0/28.7/0.3	47.7/20.0/26.2/0.7
	N4	3/26–4/9	4/2–4/16	14	46.1/31.1/18.6/0	56.3/21.8/14.9/0.3	66.9/12.0/11.0/1.0
Grower	G1	4/9–4/30	4/16–5/7	21	48.2/28.1/17.3/0	59.1/18.3/13.5/0.3	69.8/8.3/9.6/1.0
	G2	4/30–5/21	5/7–5/28	21	47.7/25.9/16.3/0	58.1/16.4/12.6/0.3	69.1/6.2/8.5/1.0
	G3	5/21–6/11	5/28–6/18	21	49.8/23.9/15.5/0	60.3/14.3/11.8/0.3	71.3/4.1/7.7/1.0
Finisher	F1	6/11–7/2	6/18–7/9	21	67.9/21.6/15.5/0	76.4/13.8/12.4/0.3	85.3/5.5/9.1/0.9
	F2	7/2–End	7/9–End	13/20	60.4/29.5/18.7/0	67.4/23.2/16.2/0.2	74.5/16.5/13.5/0.7

^a. N1–N4 stand for nursery diet phases 1 to 4; G1–G3 for grower diet phases 1 to 3; F1–F2 for finisher diet phases 1 to 2.

^b. Month/date in 2015.

^c. Phase F2 were 13 days for R4–R6 and R10–R12; and 20 days for R1–R3 and R7–R9.

^d. C/SBM/CP/AA (%) stand for yellow dent corn / soybean meal / total crude protein / supplemented amino acid in % of diet. Total CP was the sum of the CP content in all feed ingredients.

Table 3. Means for ammonia emission rates defined and used in the data analysis.

Time coverage ^a	Room coverage		
	Individual room	4-room group	All 12 rooms
2-h or 4-h sample		Group sample mean	Building sample mean
One day	Room daily mean	Group daily mean	Building daily mean
One feeding phase	Room phase mean	Group phase mean	Building phase mean
One growth stage	Room stage mean	Group stage mean	Building stage mean
Entire cycle	Room cycle mean	Group cycle mean	Building cycle mean

^a. The 2-h or 4-h were approximate air sampling intervals at gas sampling locations before April 19 and after April 19, respectively. They were used to calculate daily means but not directly reported in this paper. Measurements for ventilation calculation and other environmental variables were continuous. Outdoor temperature measurement was not related to room coverage.

Table 4. Group phase mean ammonia concentrations.

Stage	Phase	Pit				Pig living space			
		Ctrl (ppm)	T ₁ (ppm)	T ₂ (ppm)	<i>p</i> ^a	Ctrl (ppm)	T ₁ (ppm)	T ₂ (ppm)	<i>p</i> ^a
Nursery	N1	1.4 ± 0.3	1.4 ± 0.3	1.4 ± 0.3	0.45				
	N2	2.0 ± 0.4	1.8 ± 0.3	1.8 ± 0.4	0.20				
	N3	3.3 ± 1.7	2.9 ± 1.0	2.7 ± 1.0	0.07				
	N4	4.8 ± 2.2	3.6 ± 0.9	2.8 ± 0.7	< 0.05				
Grower	G1	7.1 ± 3.5	4.2 ± 1.3	2.8 ± 0.5	< 0.05	4.8 ± 1.8	2.9 ± 0.7	2.0 ± 0.4	< 0.05
	G2	6.4 ± 3.2	4.3 ± 1.8	2.6 ± 0.6	< 0.05	4.0 ± 2.2	3.0 ± 1.3	2.0 ± 0.5	< 0.05
	G3	5.3 ± 2.7	4.1 ± 1.6	2.7 ± 0.6	< 0.05	2.8 ± 0.9	2.4 ± 0.5	1.8 ± 0.3	< 0.05
Finisher	F1	5.3 ± 3.7	3.6 ± 1.7	2.4 ± 0.5	< 0.05	2.9 ± 0.9	2.5 ± 0.4	2.0 ± 0.3	< 0.05
	F2	7.5 ± 5.5	4.0 ± 2.2	3.3 ± 0.8	< 0.05	3.9 ± 1.2	3.3 ± 0.5	2.7 ± 0.4	< 0.05

^a. *p* < 0.05 indicates statistically significant differences among the means of three treated groups.

Table 5. Comparison of group phase mean NH₃ emission rates and standard deviations.

Stage	Phase	NH ₃ emission (g d ⁻¹ AU ⁻¹) ^a			<i>p</i> ^b
		Ctrl	T ₁	T ₂	
Nursery	N1	26.3 ± 13.6	23.5 ± 7.1	24.9 ± 7.8	0.613
	N2	41.4 ± 18.6	33.8 ± 9.7	31.5 ± 6.7	0.064
	N3	78.2 ± 51.3	61.4 ± 26.7	44.1 ± 15.4	< 0.01
	N4	89.5 ± 46.9	54.5 ± 20.9	37.5 ± 7.4	< 0.01
Grower	G1	99.6 ± 48.8	55.9 ± 21.5	34.0 ± 7.2	< 0.01
	G2	80.2 ± 29.7	53.1 ± 14.8	28.2 ± 6.1	< 0.01
	G3	59.0 ± 23.6	47.4 ± 13.2	26.7 ± 6.1	< 0.01
Finisher	F1	51.3 ± 22.9	35.4 ± 8.3	21.1 ± 5.8	< 0.01
	F2	58.2 ± 28.4	34.3 ± 11.0	24.6 ± 8.4	< 0.01
Cycle mean		68.9 ± 40.0	46.7 ± 19.5	29.8 ± 10.6	< 0.01

^a. group phase mean ± standard deviation^b. *p* < 0.01 indicates statistically significant differences among the means of the three groups.Table 6. Reduced NH₃ emissions of the treated groups compared with the control group.

Stage	Phase	CP diff. (%) ¹		AA diff. (%) ^a		Accum. NH ₃ (kg) ^b			Accum. diff. (kg) ^c	
		T ₁	T ₂	T ₁	T ₂	Ctrl.	T ₁	T ₂	T ₁	T ₂
Nursery	N1	2.1	4.4	0.2	0.5	0.66 ± 0.01	0.47 ± 0.01	0.60 ± 0.01	0.19	0.06
	N2	2.2	4.7	0.2	0.6	1.12 ± 0.02	0.88 ± 0.01	0.85 ± 0.01	0.24	0.27
	N3	2.5	5.0	0.2	0.6	4.38 ± 0.05	3.44 ± 0.03	2.38 ± 0.02	0.94	1.99
	N4	3.7	7.6	0.3	1.0	4.92 ± 0.05	2.95 ± 0.02	2.10 ± 0.01	1.98	2.82
	Total					11.07 ± 2.2	7.73 ± 1.48	5.93 ± 0.89	3.34	5.14
Grower	G1	3.8	7.7	0.3	1.0	7.17 ± 0.05	4.08 ± 0.02	2.41 ± 0.01	3.09	4.76
	G2	3.7	7.8	0.3	1.0	6.25 ± 0.03	4.14 ± 0.01	2.14 ± 0.01	2.11	4.11
	G3	3.7	7.8	0.3	1.0	4.96 ± 0.02	3.98 ± 0.01	2.24 ± 0.01	0.98	2.72
	Total					18.38 ± 1.11	12.21 ± 0.08	6.80 ± 0.14	6.17	11.59
Finisher	F1	3.1	6.4	0.3	0.9	4.26 ± 0.01	2.98 ± 0.01	1.73 ± 0.01	1.28	2.53
	F2	2.5	5.2	0.2	0.7	3.61 ± 0.03	2.09 ± 0.01	1.52 ± 0.01	1.52	2.09
	Total					7.87 ± 0.46	5.07 ± 0.63	3.26 ± 0.15	2.80	4.61
Cycle total						37.33 ± 2.14	25.01 ± 1.37	15.98 ± 0.67	12.32	21.35

^a. CP diff. and AA diff. are crude protein difference and amino acid difference, respectively, between the control and the specific treated group.^b. Accum. NH₃ is accumulative NH₃ mass. Mean ± standard deviation.^c. Accum. diff. is differences of accumulative NH₃ mass between the control group and the specific treated group.

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