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Review of ammonia emissions from a pig house slurry pit and outside storage

Effects of emitting surface and slurry depth

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Title:

Review of ammonia emissions from a pig house slurry pit and outside storage: Effects of emitting surface and slurry depth

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Foreword

1.1 Introduction

Pig houses and storage of slurry in under-floor pits stores are main sources of ammonia (NH_3) emissions. A recent review conducted by Griffing et al. (2007) estimated NH_3 emission of 21% of excreted TKN (total Kjeldahl nitrogen) from pig houses that utilize some form of pit/slurry system. After removal from pig houses, slurry is usually stored in outdoor tanks for 6-9 months under temperate climate conditions, thereby increasing the risk of NH_3 emissions.

Most pig buildings in Western Europe are equipped with fully or partially slatted floors. In pig houses, NH_3 emitting surfaces mostly consist of the contaminated slatted floor, solid floor and the slurry pit beneath the slats. The exposed surface area of stored slurry outside the pig houses is considered to have a substantial impact of NH_3 emissions. However, the extent of NH_3 emissions from both pig house slurry pits and outside storage depends on various parameters, which are listed in Table 1. To obtain complete knowledge of all potential parameters involved in NH_3 emissions from pig house slurry pits and outdoor storage of slurry is nearly impossible. Therefore, selected parameters that have a substantial influence on NH_3 need to be identified and evaluated based on available empirical data in the literature.

Ammonia emissions from pig houses are usually reported based on emissions per pig, per pig place and per unit of live weight. This is due to the fact that NH_3 emissions are fundamentally related to the area of the emitting surface. If NH_3 emission is calculated per pig place or per square meter, and if all assessments of the environmental impacts in relation to the areas are handled in a new area-based regulation, it would be possible to issue an environmental permit where the production is kept in the existing pig buildings even with an increased pig production. Thus, the need for frequent amendments to the permit and registrations can be avoided. Consequently, farmers can increase productivity (more produced pigs per pig place per year) without applying for new permits. Assuming that the slurry surface is the key factor influencing NH_3 emissions from pig houses, the farmer would benefit from a regulation based on surfaces compared with the existing regulation that assumes a specific percentage of the ammonium-nitrogen is lost as ammonia. However, the emissions during the storage period outside the house have to be taken into account for a whole assessment. This requires a preliminary evaluation on whether there is a scientific basis for assuming the fact that the NH_3 emission from a pig house slurry pit and outside storage facilities for pig is more dependent on the slurry surface than on the produced quantity of slurry (with the same ammoniacal nitrogen concentration) n the existing slurry-based livestock systems.

1.2 Objective

The main objective of this report was to review and gather scientific information and data from the literature to test the assumption that the NH_3 emission from a pig house slurry pit and outside storage is more dependent on the area of slurry surface than on the produced quantity or slurry (with the same ammoniacal nitrogen concentration) in the existing slurry-based livestock systems. This was based on the following specific objectives:

(i) To investigate how the magnitude of NH_3 emissions is affected by the emitting surfaces of the pit and the surface area of slurry stored outside, respectively.

(ii) To estimate if changes in the slurry depth affect NH_3 emissions in the under-floor slurry pit and outside storage, respectively.

The present review report mostly covers papers published in peer-reviewed journals and a few conference proceedings and reports. The report is restricted to NH_3 emissions from pig house slurry pits and outside storage of slurry, mostly in the European context. In this review, the term 'manure', 'manure slurry' or just 'slurry' were used interchangeably without different meaning.

Conclusion

Based on a review of available literature, the following conclusions can be made:

1. Ammonia emission from pig houses originates from slurry pits and fouled pen surfaces. The ratio between emission from the slurry pit and pen surfaces varies, but in general the major part is from slurry pits for housing system with underfloor pits.
2. The depth of slurry stored in the under-floor pit or outside storage tanks has little or no influence on the NH_3 emission rate as long as the emission surface area and the slurry properties are unchanged.
3. The floor design in the pig house strongly affects the relative emission contribution from the pen floor, but the data reported is variable. Fouling affects the ammonia emission from the pen floor, walls and slats. However, there is no clear information on the relationships between pig production rate and the degree of fouling of the pen in the pig house, including the seasonal variation.
4. The headspace height above the slurry has an effect on the ammonia emission due to higher diffusion rate and/or increased air exchange rate in the pit headspace.

Finally, we want to mention that these conclusions only are valid for ammonia and cannot be applied on other compounds, e.g. hydrogen sulfide (an indication for odor) or methane.

Future investigations

1. The overall effect of different pig production rates (different number of pigs per pen) should be investigated in replicated case-control experiments with same ventilation rate in order to test the overall hypothesis that the area-specific ammonia emission is independent of the yearly averaged density of animal units within a realistic production range.
2. The investigations should preferably be designed to quantify the relative contributions from slurry pit and pig pen, including yearly variations, as this has implications for ammonia abatement.
3. The influence of slurry height should be investigated with a focus on the effect of headspace height and air exchange rate in the headspace (rather than depth *per se*). Selected case-control studies should be carried out in experimental and production scale with sufficient replications to allow for proper statistical analyses.

2. Processes and mechanisms involved in NH_3 emission

Ammonia (NH_3) gas arising from animal husbandry derives from the animal excreta. In animal houses, NH_3 is produced from freshly deposited or stored faeces and urine. NH_3 also produced in the slurry stored outside the animal house. The quantity and distribution of slurry in the animal houses and outside storage are essential to the release of NH_3. NH_3 release from animal slurry, especially in field conditions, is a dynamic process involving numerous factors and their interactions (Table 1). Therefore, it is important to understand the rate-controlling factors in NH_3 transfer across slurry-air interface. NH_3 release is a term defined here as the process of gaseous NH_3 transfer from the immediate slurry surface into a free air stream (Fig. 1). Concentration gradients exist between the gaseous NH_3 just above the slurry surface and the free air stream.

TABLE 1. FACTORS INFLUENCING NH_3 EMISSIONS FROM SLURRY.

	Emitting surface	Factor
Pig house	Pen floor	Pig density (number and size)
		Degree of fouling
		Bedding materials
		Feed and water
		Airflow
		Air temperature
	Slurry	Bulk and interface/surface
		Total ammoniacal nitrogen concentration
		Slurry bulk and surface pH
		Slurry temperature
		Sedimentation
		Pit design
		Pit depth
	Slurry headspace 1	Headspace height
		Airflow pattern
		Air velocity
		Air volume
		Turbulence intensity
Outside storage	Slurry surface	Air temperature
		Wind speed
		Rainfall and snow
		Relative humidity
		Solar radiation

[1]See Fig. 1 for illustration of slurry and slurry headspace.

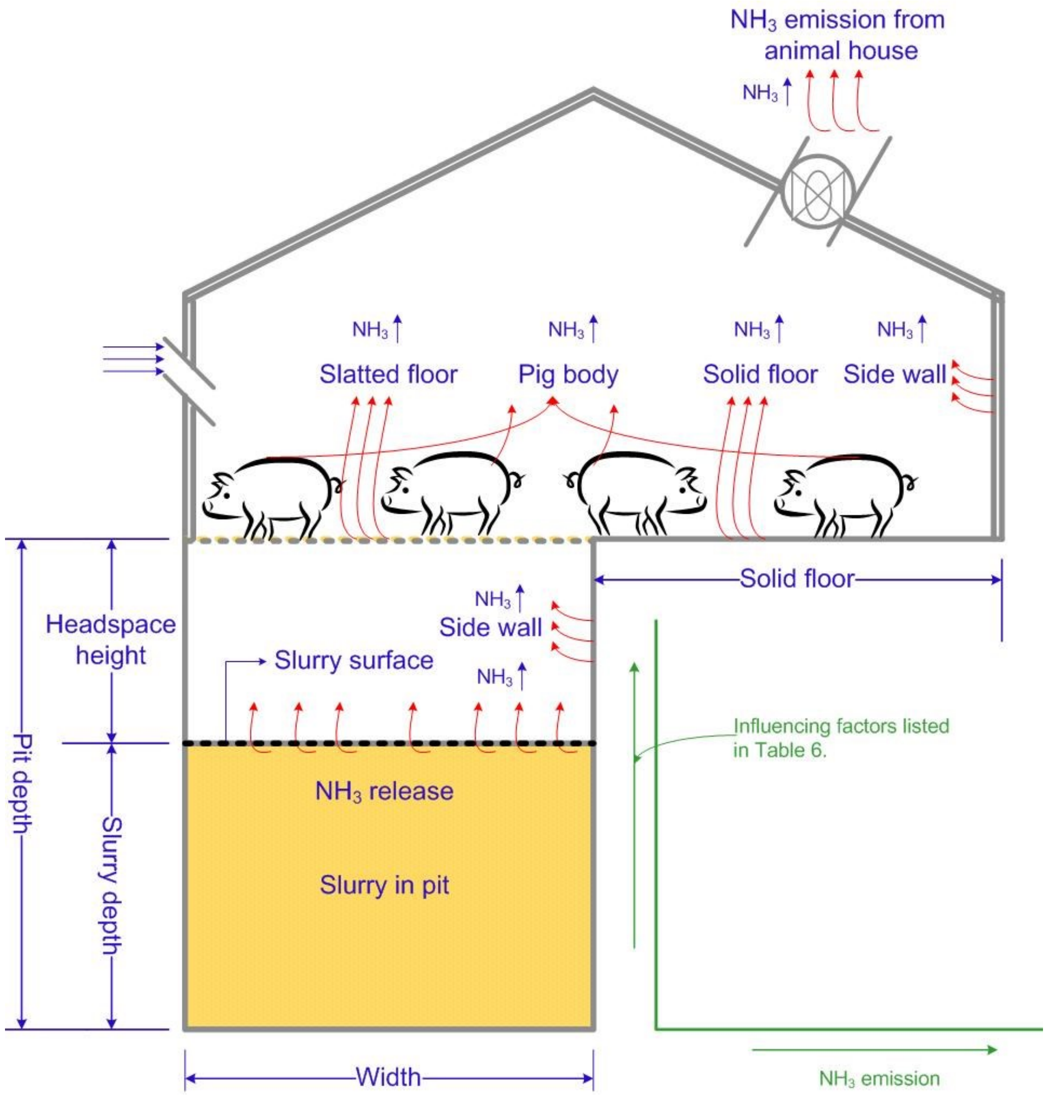

FIG. 1. SCHEMATIC DIAGRAM OF A PIG HOUSE SLURRY PIT AND SOURCES OF NH_3 EMISSIONS FROM A PIG HOUSE WITH A PARTLY SLATTED FLOOR.

2.1 Mechanisms of NH_3 release

The NH_3 release from slurry is developed on the basis of some physical insight:

- enzymatic and microbial generation of NH_3
- Chemistry of NH_3 in aqueous solution
- Diffusion mass transfer of NH_3 in slurry
- Convective mass transfer of NH_3 gas from the slurry surface to the free air stream

Some of the NH_3 in slurry is generated from biomass by means of enzymatic and microbiological activities (Ni, 1999a). The mechanism of NH_3 release from slurry can be summarised and illustrated in Fig. 2.

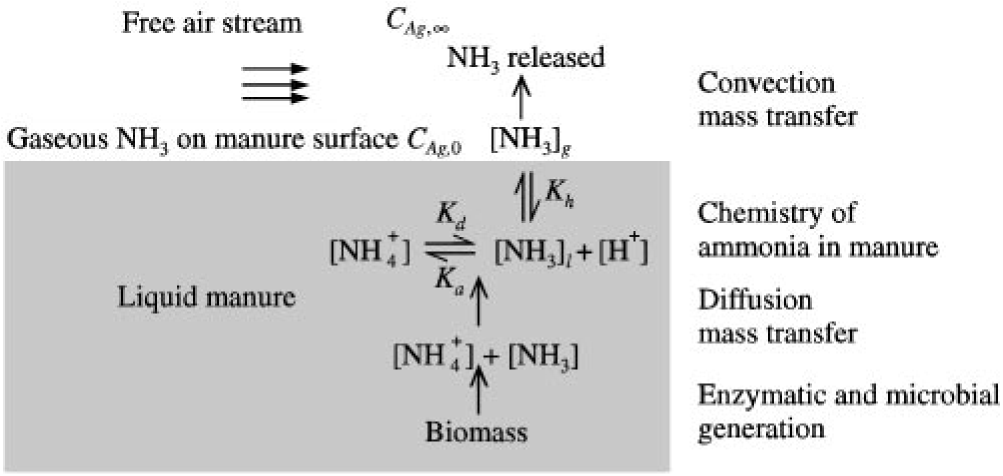

FIG. 2. MECHANISM OF NH_3 FORMATION AND CONVECTIVE MASS TRANSFER RELEASE (SOURCE: NI, 1999A).

NOTE: $[NH_3]_G$ = FREE NH_3 IN GASEOUS PHASE AT SLURRY SURFACE; $[NH_3]_L$ = FREE NH_3 IN AQUEOUS PHASE; $C_{AG,o}$ = MASS CONCENTRATION OF FREE NH_3 IN GASEOUS PHASE AT SLURRY SURFACE; $C_{AG,\infty}$ = MASS CONCENTRATION OF NH_3 GAS IN FREE AIR STREAM; K_A = ASSOCIATION CONSTANT; K_D = DISSOCIATION CONSTANT; K_H = HENRY'S CONSTANT. THE FREE NH_3 IN GASEOUS PHASE AT MANURE SURFACE IS EITHER EXPRESSED IN MOLE CONCENTRATION, $[NH_3]_G$, OR IN MASS CONCENTRATION, $C_{AG,o}$.

2.1.1 Chemistry of ammonia in aqueous solutions

In aqueous solutions like manure slurry, ammonia is present in the forms of ammonium ions (NH_4^+) and free ammonia (NH_3). Thus, the total ammoniacal nitrogen (TAN) in the solutions is the sum of the two forms: TAN = NH_3 + NH_4^+. It is only free ammonia (NH_3) that is emitted to the gas phase from the slurry surface. The release of NH_3 from the slurry to the air phase immediately above the slurry surface is driven by the differences between the gaseous ammonia $[NH_3]_g$ concentration at the slurry surface and in the bulk air. As shown in Fig. 2, the equilibrium between $[NH_3]_g$ and the concentration of aqueous ammonia $[NH_3]_l$ is characterized by the Henry's constant, K_h. The equilibrium between $[NH_4^+]$ and $[NH_3]_l$ is affected by pH. $[NH_3]_l$ can be calculated as: $[NH_3]_l = [TAN]/(1+[H^+]/K_d)$, where TAN is the measured total ammoniacal nitrogen concentration, which is the sum of the concentrations of NH_4^+ and $[NH_3]_l$. Thus, $[NH_3]_g$ at equilibrium can be calculated by: $[NH_3]_g = [NH_3]_l/K_h$.

2.1.2 Convective mass transfer

With convective mass transfer, the gaseous NH_3 at slurry surface is released into the free air stream. The rate of NH_3 release from slurry can be expressed by the following equation (Ni, 1999a) as:

$$Q_{Ar} = A \cdot h_m \cdot (C_{Ag,0} - C_{Ag,\infty})$$

Where,

Q_{AR} = rate of NH_3 release $(g\,h^{-1})$
A = area of NH_3 release (m^2)
h_m = convection mass transfer coefficient $(m\,h^{-1})$
$C_{Ag,0}$ = concentration of gaseous NH_3 in surface slurry $(g\,m^{-3})$
$C_{Ag,\infty}$ = concentration of NH_3 in free air stream $(g\,m^{-3})$

The above equation states that the rate of NH_3 release from slurry is a function of A, h_m, and the concentration difference ($C_{Ag,o}$-$C_{Ag,\infty}$). While the determination of h_m is largely empirical, the $C_{Ag,o}$ determination is more complex and consisted of several sub-models shown in Fig. 3. Determination of the convective mass transfer coefficient is an important parameter for modelling NH_3 release. A reviewed conducted by Ni (1999a) shows that h_m ranges from 11.7×10^{-3} to 1.3×10^{-6} m/s as investigated in laboratory and field experiments. It is a function of air velocity at the manure surface and air or slurry temperature. The $C_{Ag,o}$ concentration can be calculated using sub-models including Henry's constant, dissociation constant, pH change coefficient, slurry generation by animals, NH_3 generation in slurry and NH_3 diffusion in slurry.. The change of pH in the surface slurry is influenced by the releases of CO_2 and NH_3. Thus, determination of $C_{Ag,o}$ at manure surface requires several considerations.

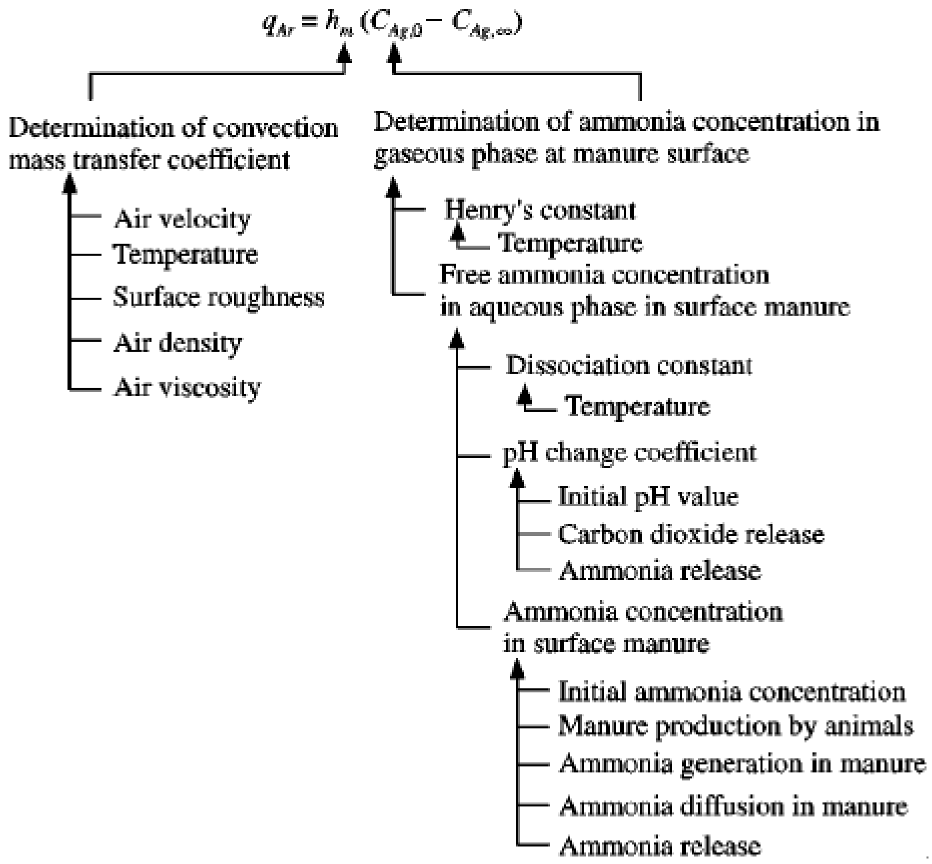

FIG. 3 GENERAL STRUCTURE OF THE MECHANISTIC MODELS OF NH3 RELEASE FROM SLURRY (SOURCE: NI, 1999A)

2.1.3 Mass diffusion

The basic theory of NH_3 release from slurry surfaces into the air is that NH_3 concentration in the slurry is higher than in the air. Equilibrium of NH_3 concentrations between the two phases is approached by release of NH_3. Two mechanisms of NH_3 transfer within the slurry are molecular diffusion and movement of gas bubbles. The slurry surface in a storage tank is open to the free air. Release of NH_3 creates a lower NH_3 concentration at the slurry surface layer than in the inside slurry layers. Consequently, NH_3 diffuses up towards the slurry surface. Thus, the NH_3 in bulk slurry can be transferred by mass diffusion if there is a concentration gradient. If the gradient is maintained by constantly supplying material to the region of high concentration and removing it from the region of low concentration, diffusion will be continue. In a single-phase system, the rate of mass transfer due to molecular diffusion is given by Fick's law of diffusion, which states that mass flux is proportional to the concentration gradient.

Gas bubbles are sometimes formed at the slurry surface, especially when slurry temperature is high. High slurry temperature results in high gas generation. However, the major proportions of the gas bubbles in the slurry are filled with CO_2 and CH_4, presumably because high CO_2 and CH_4 generation rates in the slurry and low solubility of CH_4. Rupture of the bubbles releases gases into air. In a laboratory-scale reactor experiment, Ni et al. (2009) described in details about the bubble release model and mechanisms of gases release from swine manure.

NH_3 is highly soluble in water. It is, thus, reasonable to assume that molecular diffusion is the dominant mechanism for NH_3 transfer within the slurry. High solubility of NH_3 in water allows the reasonable assumption to be made that NH_3 release from slurry depends mainly on emitting surface area than on the volume of the NH_3 solution, i.e. volume of the slurry.

2.2 Theoretical basis of NH_3 transfer from slurry surface to free air stream

There are two theories that usually used to explain the mechanisms of NH_3 release from slurry: the two-film theory and the boundary layer theory (Welty et al., 1984). Both theories are basically convection mass transfer models, which have been used previously to study NH_3 releases from manure slurry. Here the two-film theory is described.

The film theory is based on the idea that a fluid film or mass-transfer boundary layer forms wherever there is contact between two phases. The ‘Two-film theory’, also known as ‘Two-resistance theory’ or ‘Two-layer transport and release model’ based on two main assumptions (Welty et al., 1984):

- the rate of mass transfer between the two films is controlled by the rates of diffusion through the film on each side of the interface and
- no resistance is offered to the transfer of the diffusing component across the interface

Most of the resistance to mass transfer resides in the liquid films rather than in the bulk liquid. It is assumed that the two phases are in equilibrium at the plane of contact. One of the limitations of the model is that it does not include the chemical equilibria of the species involved in the entire process (Sommer et al., 2013). The ‘Two-film theory’ is a useful model for mass transfer between phases and illustrates in Fig. 4.

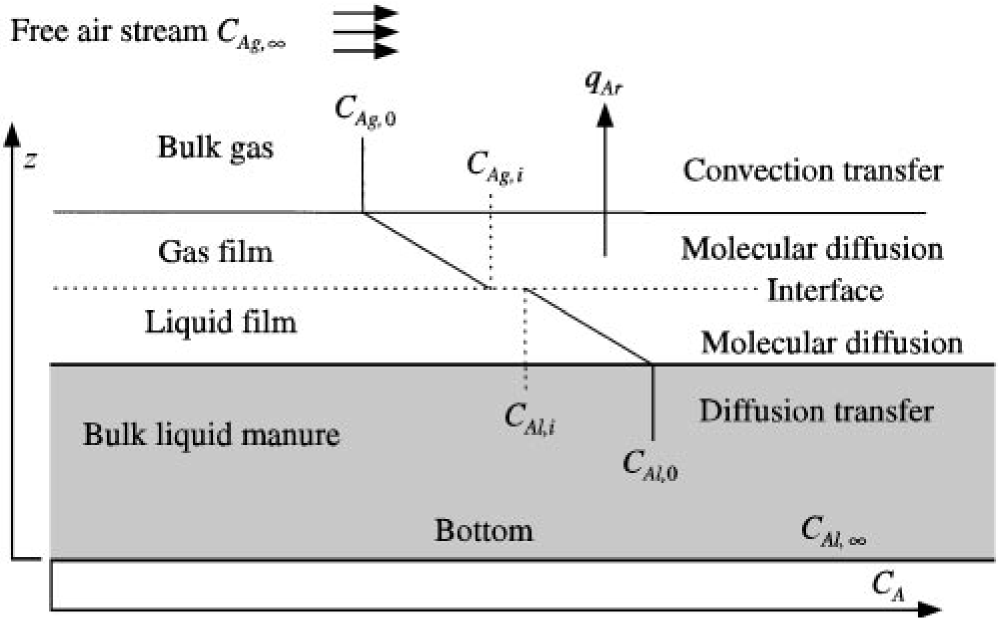

FIG. 4. THE TWO-FILM THEORY OF GAS EMISSION (SOURCE: NI, 1999A).

Note: q_{Ar} = flux of NH_3 release; z = vertical distance. Concentrations of NH_3 (C_A): $C_{Ag,\infty}$ = gas phase in free stream; $C_{Ag,o}$ = gas phase on the immediate surface of gas film; $C_{Ag, I}$ = gas phase at the interface of two films; $C_{Al, I}$ = liquid phase at the interface of two films; $C_{Al,o}$ = liquid phase on the immediate surface of liquid film; $C_{Ag,\infty}$ = liquid phase at the bottom of the bulk manure.

2.3 Measuring instrument and technique

The calculation of NH3 emission rate requires measurement of air exchange rate and the NH3 concentrations in the inlet air and at the outlets. The correct measurement of gas concentrations and air/ventilation exchange rates is crucial for the validity of the results. It is essential that the measurement instrument, its working principle, calibration and accuracy are clearly described in the paper. However, very few studies included this information. Thus, it is important to use reliable measurement methods and accurate ventilation control to reduce experimental uncertainty.

3. Factors influencing ammonia emissions from slurry

3.1 Pig house

3.1.1 Floor type

Floor type was reported to have influence on NH_3 concentration in and emissions from pig houses (Thompson et al., 2004). . Van der Peet-Schwering et al. (1999) reported that ammonia emissions with partly slatted floor was 2.5 kg per pig place and with fully slatted floor was 3.0 kg per pig place in Netherland. The authors also suggested that reducing emitting surface could decrease NH_3 emissions from pig houses.

The amount originating from the slurry channel probably varies with conditions in the house, for example, the slatted floor area and material and the air movements in the house. A study in the Netherlands has shown that NH_3 emissions can be reduced by 20% if the slatted floor area for weaned pigs is decreased from 50% to 25% of the pen area. The corresponding reduction of NH_3 emissions for fattening pigs is 10% (Aarnink et al., 1996). The authors estimated that with 25% slatted floor, 40% of the ammonia emissions were from the pen floor and 60% were from the pit. However, with 50% slatted floor, 23% of the emissions were from the pen floor and 77% were from the pit. It indicates that the contribution (relative to the pit emission) from a pen floor with larger solid floor area (25% slats) is higher due to a bigger fouling area and/or urine on the solid floor. However, it should be kept in mind that the total emission from a fully slatted floor is higher than from a partly slatted floor.

Measurements in a fattening pig house with 40% slatted floor area and scrapers under the slats have shown that 47% of the NH_3 emissions originate from the slurry channel. This proportion appears to increase with larger air exchange rate (Botermans et al., 2010).

Aarnink and Wagemand (1997b) report that between 25% and 75% of NH_3 emissions in a pit system originate from the slurry pit below the floor, while the rest comes from the fouled portion of the floor. Hoeksma et al. (1992) calculated NH_3 emissions of about 2/3 from the slurry pit and 1/3 from the pen floor (63% slatted). Aarnink and Elzing (1998) estimated that 70% of NH_3 emissions occurred in the slurry pit using their mechanistic model. A recent Danish study in a summer period with acidification of slurry in the slurry pit to a pH value of 5.7 shows a 71% reduction in NH_3 emission compared with an unacidified control slurry with a pH value of 7.6 (Pedersen and Albrechtsen, 2012).

Effects of fouling on ammonia emissions were discussed by Ni et al. (1999b). Ni et al. (1999b) studied the effect of manure distribution on the pen floor on ammonia emissions from a commercial fattening pig house. The results revealed that the ammonia emissions were linearly increasing with the floor contamination (0: clean, 1: fully dirty) because the fresh manure had a quick release property of ammonia. The bigger floor contamination also improved the effect of ventilation rate on ammonia emissions. With bigger floor contamination, the ammonia emission could be increased 30% under the same ventilation rate. Therefore, the surface area of manure on the pen floor had the same significance as that in the manure pit for ammonia release process. In addition, the ammonia emission was positively related to the frequency of pig's urines (Aarnink et al., 1997a) and higher indoor temperature because higher indoor temperature lead to larger floor contamination (Ni et al., 1999b).

As to the emission from the slatted floor, it is related to the width of the slats and the width of the gaps. The width of the gaps was found to be important to the faeces removal (Aarnink et al., 1997a). The quicker the urine and urease can be removed from the pen floor, the less ammonia will be released. Besides, the side surface area of the slats also affect the ammonia emissions (Pedersen & Ravn, 2008), when the ammonia solution/urine sticks to the surface. In this study, twelve tested floors were selected and constructed to examine and compare different alternatives of slatted floors and one solid floor on ammonia emissions in Denmark. The tests were conducted in a wind tunnel with cross section of 0.5m x 0.5 m. A standard ammonia water with ammonia content of 8% was used for experiments. The procedure for measuring the ammonia emission was to wet the floor surface completely by brushing the surface. Depending on the shape of the slatted floors the sides of the test floors were, to some degree, wetted too. The results are summarized in Table 3.

Table 3. Ammonia emission in mg per 0.24 m² floor surface (SD=standard deviation) (source: Pedersen & Ravn, 2008).

No.	Material	Type	Description	NH_3 emission	SD
1	**Polyethylene**	Slatted	Commercially available	174	20
2		Slatted	As floor 1, with sand incorporated on the surface	195	51
3		Slatted	As floor 1, with rubber strips on the surface	217	29
4	**Concrete**	Solid	Flag with a slightly profiled surface	192	24
5		Slatted	Commercial short element	272	82
6		Slatted	Commercial long element	300	51
7		Slatted	As floor 6, with brushed surface	432	103
8		Slatted	With 50% concrete replaced by plastic granules	297	121
9		Slatted	Studded plastic cover	393	84
10	**Cast iron**	Slatted	Commercial	181	50
11		Slatted	As floor 10, with polished surface	163	28
12		Slatted	As floor 10, mechanically treated with grooves	184	93

The results showed that the ammonia emission from solid concrete (flag) was only 57% compared to concrete slatted floors, because the total exposed surface was smaller than that for slatted floors, since the sides were wetted too. The ammonia emissions from slatted floors of concrete wetted with ammonia water were nearly twice as the ammonia emission from slatted floors of plastic and cast iron.

Hamelin et al. (2008; 2010) investigated twelve optimal low-emitting concrete slats (including control) on ammonia emissions in an environmental emission chamber in Denmark. A urea-urease solution was used to foul the slats. A 3*2*2 factorial treatment design was applied, with three replications, so the 12 combinations were tested per repetition. Three factors were tested: the slat section shape, the presence (or absence) of a notch along the slat, and the presence (or absence) of a smooth epoxy coating applied on the slat sides and bottom faces. The results revealed that only the presence of a notch had a significant effect on NH_3 emission reduction between 23% and 42%. The shape of the cross section of slats had little effect on ammonia emissions. The limitation of these two studies is that ammonia solution or urea-urease solution were used instead of pig manure to avoid the uncontrolled variation of manure in each test. In addition, the tests were conducted in a wind tunnel or an environmental chamber where the airflow patterns were totally different from the flow in a full scale pig house. Therefore the results achieved from these two studies have the difficulty in extending the application in the pig houses. More investigation of this issue in full scale pig barn should be further conducted.

NH_3 emissions from various animal housing systems for fattening pigs can be compared with a reference case with fully slatted floor. Ammonia emissions for this type of system in Europe lie between 2.4 and 3.0 kg per pig place per year (Botermans et al., 2010). Animal housing systems with partly slatted floor, concrete slats and mechanical scrapers give 40 % lower NH_3 emissions, i.e. 1.4-1.8 kg per pig place per year (ECE, 2007). Partly slatted floor, concrete slats and vacuum slurry extraction reduce NH_3 emissions by 25 %. Straw bedding in pens can increase NH_3 emissions by 0-33 % compared with the reference pen (BREF, 2003). Ammonia emissions from pens with a straw-flow system have been studied in Austria by Amon et al. (2007) and have been found to be 2.2 kg per pig place per year, i.e. around 25 % lower than those from the fully slatted reference system. In this system, the straw is mixed with dung, transported down a slope and out of the pen to a scraped passage by pig motion.

A few studies on the effect of different floor systems on ammonia emissions obtained different conclusions. For example, Guingand & Granier (2001) studied the effect of partially (50%) or fully slatted floor during growing period of pigs on ammonia emissions in France in two identical pig pens except for the type of pen floor. The results showed that the ammonia emission with partially slatted floor was 11.2 g pig^{-1} day^{-1} while the ammonia emission with fully slatted floor was 6.2 g pig^{-1} day^{-1}. These results were not in accordance with the studies in Netherland.

Philippe et al. (2007b) studied the effect of fully slatted floor and straw flow system on ammonia and greenhouse gaseous emissions in Belgium. The manure in the pit was removed at the end of each fattening batch. With a straw-flow system, liquid from manure was automatically pumped from the scraped passage into a hermetically closed tank and the rest of the manure was manually scraped every day and stored in the room while the manure heap was removed once a month. The results revealed that the ammonia emission with fully slatted floor was 5.0 g pig^{-1} day^{-1} while it was 13.3 g pig^{-1} day^{-1} with the straw-flow system. Amon et al. (2007) also studied a straw-flow system in Austria and reported considerably lower ammonia emissions, which were 2.1 and 1.9 kg pig^{-1} $year^{-1}$ without and with daily manure removal. The reason for the contradictory results may be related to different removal frequency of the straw and the areas per pig, which were 0.79 m^2 pig^{-1} (Philippe et al., 2007b) and 1-1.3 m^2 pig^{-1} (Amon et al., 2007). Part of the ammonia emission was emitted from the manure heap as argued by Philippe et al. (2007b).

Kavolelis (2006) studied three types of pig house system on ammonia emissions in Poland. The three pig house systems were a concrete floor system, a fully slatted floor system and a straw based litter system. For concrete floor, the manure was manually pushed to the manure channel every day. For litter, the manure was removed every week by a tractor. The results showed that the lowest ammonia emission occurred at the house with the straw-based litter system with 6±2 g pig^{-1} day^{-1}, followed by the fully slatted floor with 7±2 g pig^{-1} day^{-1} and the concrete floor with 8±3 g pig^{-1} day^{-1}. The results from this study was not in accordance with the results from Philippe et al. (2007a), who reported that the ammonia emission with fully slatted floor (15.6%) was 6.2 g pig^{-1} day^{-1} while it was 13.2 g pig^{-1} day^{-1} with a straw based deep litter system. One of the main differences in the manure management was that the manure in the pit and the straw was removed at the end of each fattening batch in this study.

According to the above literature review, it is difficult to compare and generalize all the data from different studies due to the different units used (e.g. kg per pig place per year, g pig^{-1} day^{-1}), different designs of pig house, ventilation system control, management system, climate zones (different countries) etc.

For pig houses, it can be summarized based on available literature that:

- The slurry pit contribution to the total ammonia emission is highly variable and depends primarily on floor type, but also on ventilation rate (therefore also seasonally variable).
- The pen floor contribution depends strongly on the soiling of the surfaces, which is also seasonally variable to some extent (e.g. more soiling under warm conditions).
- There is no clear information about the effect of pig production rate on floor soiling and hence on the pen floor contribution to the total emissions.
- The effect of litter on ammonia emission is not clear since contradictory results have been reported.

3.1.2 Emitting surface in the pit

From a mass transfer viewpoint, reducing the emission surface area could lead to a reduction of emissions. Doorn et al. (2002) prepared a report for USEPA and summarized the NH_3 emissions from European countries. The results are listed in Table 4. The results show that different designs of housing system could reduce the NH_3 emission from 2.5 kg pig^{-1} year^{-1} (with 50% slatted standard floor and pit area of 0.40 pig^{-1} per animal place) to 1.0 kg pig^{-1} year^{-1} (with sloping floors and a pit area of 0.18 m pig^{-1} per animal place).

TABLE 4. RELATIONSHIP BETWEEN NH_3 EMISSIONS AND PIT AREA (SOURCE: DOORN ET AL., 2002).

Type of pig/ pit system	Pit area (m^2 per animal place)	Ammonia emission (kg NH_3 per animal per year)
Finishers		
• standard (50% slatted)	0.40	2.5
• separate manure gutters	0.29	1.8
• sloping floors	0.18	1.0
Gestating sows		
• standard individual confinement	1.1	4.2
• narrow manure gutter with metal slatted floor	0.4	2.4
Farrowing sows		
• standard fully slatted floor	4.1	8.3
• shallow manure pit with gutter	0.8	4.0

Mol & Ogink (2004) mentioned on type of emission-reducing pig housing systems with reduced emitting surface of manure in the pit. This was achieved by having a V-shaped slurry culvert, which decreases the slurry surface area (Botermans et al., 2010; BREF, 2003; ECE, 2007). The V-shaped sides must have a smooth surface so that the slurry does not adhere to the side surface. For fattening pig pens the specification is that the sloping side facing the pen lying area must have at least 45° slope and that the other sloping side on the opposite side must have at least 60° slope. This decreases slurry surface area in the slurry channel to maximum 0.18 m^2 pig^{-1} (Botermans et al., 2010). It was reported that this measure gives a 60% reduction in NH_3 emissions compared with the reference pen (ECE, 2007). This indicates that reducing the emission surface area in the pit leads to lower ammonia emissions, but attention to the slope of the culvert must be paid. A good design of the culvert's slope can minimize the manure sticking on the side surfaces of the slurry channel, otherwise the total emission surface in the pit could be enlarged due to this.

3.1.3 Slurry depth

Most pig buildings in Western Europe are equipped with fully or partially slatted floors. For a partly slatted floor, however, the ratio of slatted to solid floor area can be varied. When the fresh pig slurry (consisting of a mixture of urine and faeces), as excreted by pigs, drops on the floors, a large fraction of the slurry enters immediately into the pit through the slatted openings. However, some quantity of slurry can be retained in the fouled portion of the floor, including the pigs' body. In a study of fattening pig house with a partly slatted floor and a mechanical ventilation system, Ni et al. (1999b) found that the quantity of slurry fouled on the wall, on the pig bodies and on the slatted floor is insignificant as compared with the slurry in the slurry pit and on the solid floor.

The quantity (or volume) of slurry in the pit is determined by the slurry depth. The slurry depth is the vertical distance from the pit bottom to the slurry surface (Fig. 1). The slurry depth is directly proportional to the quantity of slurry in the pit. The slurry depth in the pit increases until the pump-out of the slurry. Increasing slurry depth reduces headspace in the slurry pit and vice versa. The headspace is the area between the slurry surface and the slatted floor, as shown in Fig. 1. In a pig house, the under-floor slurry pit is the final destination of all slurry and water. The slurry in the pit is the important location of NH_3 emission source, since a substantial part of freshly produced slurry is usually stored in the pit for some time. Thus, the variations in the slurry depth in the pit might have some influence on NH_3 emission rates.

The influence of slurry depth upon NH_3 emissions, however, has not been widely investigated. Based on the previous section, it is reasonable to assume that the slurry pit is the major source of NH_3 emission from pig houses, although the contribution is highly variable among different studies. Those studies did not include the effect of slurry depth as a single factor on NH_3 emission from slurry pits.

Few studies have reported on the relationship between NH_3 emission rate (and airflow pattern) and the slurry depth and the results obtained have been mixed. In a pit-ventilated scale model swine confinement building, Schulte et al. (1972) found that the depth of manure in a pit caused significant differences in the mean air velocities above the slatted floors. However, the magnitude of the effect depended upon the baffled slot inlet ventilation system. This result contradicts the observation by Buller and Hellickson (1978) that there is no effect of manure depth on airflow patterns above or below the floor in a scale model pit-ventilated building. However, both are model studies with differences in experimental design between the studies.

In a one-half scale model swine pit-ventilated confinement barn, Buiter and Hoff (1998) found that manure depth significantly affected NH_3 levels and gas distribution in the airspace above and below the slatted floor. However, the authors did not measure the airflow pattern, air velocity and turbulence intensity at the emission surface. To simulate ammonia production from the manure surface, those authors used gaseous ammonia and supplied to the pit area of the model. It has been reported that frequent emptying of slurry channels with inclined walls reduce NH_3 emissions by up to 50% because the surface area of the slurry is reduced due to lowering the depth of slurry (Groenestein and Montsma, 1993). However, Ni et al. (1999b) did not observe good correlation (Fig. 5) between the measured NH_3 emission rates and the manure depths in a 2-m deep under-floor manure pit with vertical slurry channel walls. The authors recorded minimum and maximum manure depths of 0.16 and 1.16 m, respectively. However, slurry was pumped out from the pit three times during the entire experiment of 135 days. In their study, the studied pig house had a capacity of 70 fattening pigs and was divided into six pens. Recently, Ye et al. (2011) conducted a study to determine the effect of slurry depth on NH_3 emissions from a pig house slurry pit and found no good correlation between the measured NH_3 emission rates and the slurry depths. To avoid the effect of animals, however, the authors used empty full-scale pig rooms with clean slatted floors and pig slurry in the pit. The reason for using clean pen floor was to avoid interference from floor emission. The experimental rooms used in their study were mechanically ventilated, fattening rooms with the differences in floor and pit systems between the two rooms. Table 5 summarizes empirical values of correlation coefficients, r for NH_3 emission rate and slurry depth reported in the literature.

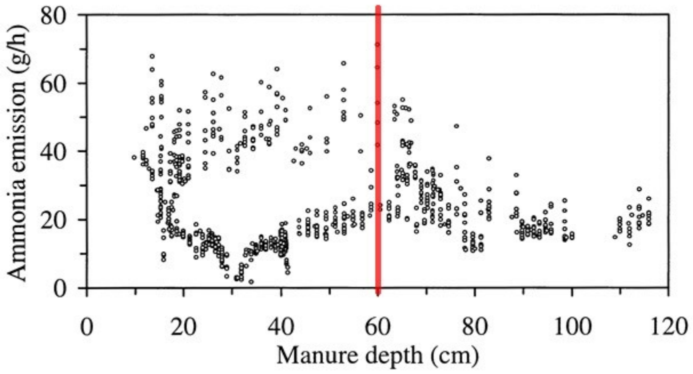

FIG. 5. RELATIONSHIP BETWEEN THE NH_3 EMISSION RATE AND THE MANURE DEPTH IN MANURE PIT OF FATTENING PIG HOUSE (SOURCE: NI ET AL., 1999B). THE RED-COLORED VERTICAL LINE SHOWS THE MAXIMUM DEPTH OF SLURRY THAT CAN TYPICALLY BE FOUND IN A PIG HOUSE SLURRY PIT IN DENMARK.

TABLE 5: EMPIRICAL VALUE OF CORRELATION COEFFICIENT, *R* BETWEEN NH_3 EMISSION RATE AND SLURRY DEPTH IN THE PIT.

Slurry/manure depth (m)	**Correlation coefficient, *r***	**Scale**	**Reference**
0.10-1.16	-0.143	Commercial fattening pig house	Ni et al. (1999b)
0.026-0.082	-0.115	Scale model (1:12)	Ye et al. (2008)
0.15-0.65	-0.125	Experimental pig pen	Ye et al. (2011)

In a study of the effects of the age of the slurry from finishing pigs, Jonassen (2012) compared emission from 6 pens with fully-slated floor with pits with varying age (1 to 6 weeks) of slurry (which were linearly correlated with the depth) and did not find any significant effect on the ammonia emission from the pens.

The headspace height in a slurry pit depends on the slurry depth, since increasing slurry depth reduces headspace in the slurry pit and vice versa. Thus, the change of headspace height due to change in slurry depth could affect the air volume and air exchange rate in the under-floor slurry pit (Ni et al., 1999b; Ye et al., 2008; 2009). This might have some influence on the airflow patterns inside the pit as well as NH_3 emission from slurry surface. In lab experiments using a 1:12 scale model of a growing/finishing pig house with pig slurry in the pit and a clean slatted floor with various floor openings areas, Ye et al. (2008a) found the maximum NH_3 emission occurred at 0.026 m compared to 0.05 m and 0.082 m headspace heights, with minimum emissions observed at the 0.05 m. Three headspace heights of 0.026, 0.050 and 0.082 m, three slatted floor opening ratios of 100, 33.3 and 16.7%, four ventilation rates ranging from 0.005-0.020 $m^3 s^{-1}$ and a constant inlet opening height of 0.005 m were tested in their experiment. The 100% opening ratio was used as the reference treatment, which meant that the headspace was an integral part of the scale model room air space. No good correlation between the measured NH_3 emission rates and the slurry depths was established in their work, as determined by the correlation coefficient, *r* (Table 5). Those authors suggest that reducing the headspace height increases the air exchange rate in the headspace, thereby increasing NH_3 emission from the 0.026 m headspace height.

The influence of ventilation rate, air velocity and turbulence level on NH_3 emissions has been reported by few studies (Elzing & Monteny, 1997; Ye et al., 2008). For example, Ye. et al. (2008) reported the influence of these parameters on NH_3 emission from aqueous solution surface; however, variations in the headspace height in the pit were not considered. Ye et al. (2009) performed a similar study to Ye et al. (2008) to investigate how the airflow characteristics at the slurry surface is affected by different ventilation rates, slatted openings and headspace heights in pit and explained NH_3 emission results reported by Ye et al. (2008). While Ye et al. (2008) used pig slurry, Ye et al. (2009) tested water in the pit. They found that the mean turbulence intensity decreased with increasing ventilation rate due to increasing mean air velocity above the slurry surface for 0.050 m and 0.082 m headspace heights. However, they did not find significant difference in the mean turbulence intensity for 0.026 m headspace height and suggested that the NH_3 emission was mainly due to the air velocity. Based on statistical modelling, both studies (i.e. Ye et al., 2008 and Ye et al., 2009) reported that that NH_3 emission rate was more sensitive to ventilation rate than to the slatted floor opening ratio and headspace height in the pit.

Available literature data (Table 5) suggest that the slurry depth or quantity of slurry in the pit has little or no influence on the NH_3 emission rate. However, most of the studies, except for Ni et al. (2009b), reviewed here were conducted using scale model animal houses with water or pig slurry in the pits and numerous variants and adaptation. Consequently, a range of emission levels for both partially and fully slatted floors can be found in the literature. Regardless of slurry pits in pig production systems across the farms, the change of slurry depth in the pit will only affect the quantity or volume of slurry in the pit; but the total surface of the pit will remain unchanged. It is usually considered that the extent of NH_3 losses increases with the area of the slurry surface. Therefore, it is likely that the NH_3 emissions from the slurry surface would not be affected by the change of slurry depth in the pit. However, this hypothesis lead to the interesting research question of whether the change of headspace height due to change in slurry depth would influence the rate of NH_3 emissions from the slurry surface. As mentioned earlier, Ye et al. (2008; 2009) reported that the maximum NH_3 emissions occurred at 0.026 m compared to 0.05 m and 0.082 m headspace heights. Their data suggest that a smaller headspace between the slats and the surface of slurry (due to increasing slurry depth) increases air turbulence and the release of NH_3. However, those authors kept the slurry depth constant and changed the headspace heights by adjusting the height of the top part relative to the manure container in a model pig house. Furthermore, they did not validate the results in a full-scale pig house. Based on their data obtained from the scale model study, it is difficult to draw a conclusion that the NH_3 emissions increase with decreasing headspace height due to high air velocities occur at the emissions surface.

There has been little research to date on how the change of the headspace height due to the change in slurry depth affects the airflow pattern, air velocity and turbulence level at the emission surface, and their interactive influences on NH_3 emission from slurry surface in the pit. Ni et al. (1999b) explained that the poor correlation (correlation coefficient of -0.143; see Table 5) between the steady state NH_3 emission rates and slurry depths was probably due to the mechanism of convective NH_3 mass transfer from the manure to a free air stream, in which the surface area of NH_3 release is directly proportional to the rate of NH_3 release. The significance of the differences between turbulence intensities for various floor types and slurry depths has not been well investigated. The processes involved in NH_3 release from slurry in animal houses and stores outside the animal houses are very complex and described in section 2.

The depth of slurry in the pit varies across Europe depending on pig density inside the house. A typical Danish pig house has a maximum slurry depth of 0.6 m (60 cm), which is half of the slurry depth studied by Ni et al. (1999b) (shown by the red-colored vertical line in Fig. 3). Therefore, the study conducted by Ni et al. (1999b) may not be directly relevant to the Danish situation. Frequent slurry discharge had a small but significant effect on NH_3 emissions from a pig section with fully slatted floor. An 11% reduction with frequent discharge was observed (Jonassen, 2012). The average manure height was ~5 cm with frequent discharge, whereas in the control the height was between 5 and 35 cm (i.e. much higher than 5 cm on average). The results indicate that the slurry height may have a small effect, but decrease in surface pH following disturbance by discharge as well as different average age of the slurry could also be factors. Under confined pig production, slurry is produced on a nearly continuous basis and the rate of slurry accumulation in the under-floor pit increases with time. This renews the surface layer of the stored slurry from which NH_3 is release, which diminishes the effects of time. Since the under-floor slurry pit acts as a continuous fed system, the effects of time (in terms of slurry depth, slurry age and pH levels) on NH_3 emission from a pig house slurry pit need further investigation.

Preliminary meta-analyses on the available empirical data suggest that the slurry depth is not a critical factor that determines NH_3 emissions from the surface of slurry in the pit. This suggests that increasing pig density in existing fully or partly slatted pig houses and subsequently produced large amounts of slurry in the pits (hence higher slurry depths) would not promote the release of NH_3 from the slurry surface, since the total surface of the pit will remain unchanged.

3.2 Outside slurry storage

In pig houses, slurry is deposited directly into the under-floor pit through partially or fully slatted floors. However, storing slurry under the floor of the pig houses can be limited because of the necessary large volumes implied. Stored slurry in pig houses can also lead to the release of noxious gases (e.g. H_2S) when stirred or emptied. If slurry pits are not well managed, it threats to the air quality indoors and to the environment. Because of their irritant and toxic nature, both NH_3 and H_2S gases are of major concerns to the health of workers and pigs present in indoor environments.

There are increasing efforts to remove slurry from pig houses and store it outside. The storage facilities outside the pig houses can take several forms such as an above-ground metal tank, a concrete tank, or an earthen storage (also known as below-ground, e.g. lagoon or pit). Across Europe, above-ground slurry stores alongside the pig houses are the most common technique for slurry storage. In Denmark, for example, pig slurry is mainly stored in outdoor concrete storage facilities. Due to a short time window for application to agricultural land under temperate climate conditions, slurry is usually stored for 6-9 months. However, the length of storage time varies across Europe depending on the non-growing winter period. In colder areas of Scandinavia it may need more than nine months to store slurry outside.
There is an apparent scarcity of quantitative data on NH_3 emissions from the pig slurry stored outside of the pig house. Furthermore, there is considerable variation in results reported in the storage studies reviewed here. Table 6 summaries the variation in storage studies in terms of pig types, slurry volume and initial properties such as DM, pH and TAN, and duration of storage. Thus, the reported results do not provide an accurate basis of comparing one slurry storage design with another. The variability of the NH_3 emissions from outside storage of slurry is influenced by many factors and summarized in Table 1 in section 2.2.

Several options are available to reduce NH_3 emission during slurry storage. One of the options is covering slurry stores to reduce emissions by increasing the surface's resistance to NH_3 volatilisation or by reducing the emitting surface, heating and turbulence at the slurry surface. Both impermeable and permeable, including bio-cover (e.g. straw, cornstalks, sawdust, wood-shaving, etc.) have been suggested for reducing NH_3 emissions. When these methods were studied and NH_3 emissions reported for a control slurry storage (i.e. no slurry cover), and for a slurry storage utilising the NH_3 reduction methods (different slurry covers), only the control data were listed in Table 6. Where necessary, the reported slurry volume and NH_3 emissions were converted to m^3 and g NH_3-N m^{-2} d^{-1}, respectively.

The NH_3 emissions for the studies reviewed here varied between 0.40 and 8.62 g NH_3-N m^{-2} d^{-1} (Table 6). Data show that there is a considerable variation in the pig slurries and their initial properties such as DM (3.0-8.4%) and TAN contents (1.1-4.3 g kg^{-1}), slurry volume (0.06-600 m^{-3}), duration of storage (1.5-6 mo), experimental design (e.g. summer vs winter; with stirred vs no stirred) and gas measurement methods used in reported storage studies. This could easily have contributed to the differences in NH_3-N emissions between the studies.

Balsari et al. (2007) measured NH_3 emissions from uncovered pig (farrow-to-finish) slurry storage using the funnel technique on the slurry surface and floating wind tunnels. They found that the rate of NH_3-N emission is significantly influenced by the temperature of the slurry top layer. However, NH_3-N emissions data, as obtained by using a funnel technique, do not represent the real environmental conditions due to very low wind speed under the funnels. This suggests that NH_3 emission estimates from slurry storage depends also on measuring method used. However, those authors claimed that the results obtained by the wind tunnel are representative of NH_3-N losses under real environmental conditions.

Berg et al. (2006) reported NH_3-N emission of 4.2 g N m^{-2} d^{-1} from uncovered storage of pig slurry. It appears that lower pH value is necessary to reduce NH_3 emissions. However, their results need to be validated in a full-scale storage facility.

Petersen et al. (2013) conducted a pilot-scale storage facility to quantify NH_3-N emission from finishing pig slurry storage (uncovered) during the Danish winter and summer seasons. They found higher NH_3 emissions during summer than during winter. This is likely due to the effects of temperature.

TABLE 6. AMMONIA EMISSIONS (G NH_3-N M^{-2} D^{-1}) FROM STORED PIG SLURRY OUTSIDE OF THE PIG HOUSES (WHERE NECESSARY, THE REPORTED SLURRY VOLUME AND NH_3 EMISSIONS WERE CONVERTED TO M^3 AND G NH_3-N M^{-2} D^{-1}, RESPECTIVEL). DM = DRY MATTER; TAN = TOTAL AMMONICAL NITROGEN.

Pig type	Treatment details	Slurry volume (m^3)	g NH_3-N m^{-2} d^{-1}	Storage period (d/mo)	Initial slurry characteristics			Measurement method	Reference	Country
					DM %	pH	TAN (g kg^{-1})			
Farrow-to-finish pigs	Mean air temperature (°C) = 14.2; mean air velocity (m s^{-1}) = 0.9	243.4	1.30	Sep-Jun (6 mo)	3.7	7.8	1.2	Funnel system floated on the slurry surface	Balsari et al.(2007)	Italy
	Mean air temperature (°C) = 6.3; mean air velocity (m s^{-1}) = 0.5	243.4	0.69		3.9	7.7	1.1	Same as above		

	Mean air temperature (°C) = 14.0; mean air velocity ($m\ s^{-1}$) = 0.7	243.4	1.24		4.1	7.4	1.1	Same as above		
	Mean air temperature (°C) = 24.8; mean air velocity ($m\ s^{-1}$) = 0.9	243.4	2.04		3.8	7.7	1.4	Same as above		
	Mean air temperature (°C) = 24.8; mean air velocity ($m\ s^{-1}$) = 0.9	243.4	8.62		3.8	7.7	1.4	Floating wind tunnel		
Pig slurry	Stored in open container; closed and ventilated only during gas measurement	0.072	4.2	162 d	5-8	7.2	3.9	Ventilated chamber	Berg et al. (2006)	Germany
Finishing	Winter-with sheltering to intercept precipitation	4	0.72	45 d	3.3	7.4	2.3	Forced ventilation	Petersen et al. (2013)	Denmark
	Winter-without sheltering to intercept precipitation (open storage)	4	0.40	45 d	3.0	7.5	2.5			
	Summer-with sheltering to intercept precipitation	4	3.1	58 d	7.4	7.4	4.0			
	Summer-without sheltering to intercept precipitation	4	2.0	58 d	8.4	7.4	4.3			

	(open storage)									
Pig slurry	Sorted slurry stirred once a week; duct wind speed: 4.4 m s^{-1}; air temp = 7 °C	4	3.9	Sep-Dec (4 mo)	4.6	7.3	4.1	Wind tunnel	Sommer et al. (1993)	Denmar k
	Stored slurry stirred once a week; duct wind speed = 4.0 m s^{-1}; air temp = 6 °C	4	4.6	Feb-Jun (5 mo)	7.4	7.4	4.2	Wind tunnel		
Farrowing-fattening	Autumn store with intermittent stirring	400	4.1	6 mo	4.2	-	2.8	Dynamic chamber technique	Loyon et al. (2007)	France
	Summer store-without stirring	600	6.7	6 mo	4.9	-	2.5			
Aged fattening pigs	During 15 consecutive weeks in summer, vessels were stored in a roofed space	0.8	4.0	15 wk	-	-	-	Dynamic Chamber	Moset et al. (2012)	Spain
Swine	Containers were buried in the ground to simulate ponds (uncovered)	1.06	6.7	19 Feb-23 Dec (10 mo)	3	8.4	-	Calculated	Yagüe et al. (2011)	Spain

Sommer et al. (1993) measured NH_3-N emissions from storage of slurry tanks using wind tunnels in Denmark. The slurry stored in uncovered slurry tanks were stirred once per week. They reported that the rate of NH_3 emissions depend on convective transport of atmospheric NH_3 from the slurry surface and the concentration of atmospheric NH_3 above the slurry surface. They observed high NH_3-N emissions due to stirring the slurry once in a week. Those authors explained that mixing increased the TAN concentration in the surface layer; however, they did not provide data. Based on 6 months of storage pig (farrowing-fattening) slurry under French climate conditions, however, Loyon et al. (2007) found that stored slurry with stirring resulted lower NH_3 emission than slurry without stirring (Table 6), which contradicts findings of Sommer et al. (1993). The low NH_3-N emission due to stirring of slurry can be explained by mixing which reduces the surface pH and thus the emission. Without mixing, the surface layer pH increases to a stable level, which is significantly higher than the bulk pH (Bildsoe et al., 2014).

Preliminary meta-analyses on the available empirical data suggest that exposed surface area of stored slurry have a substantial impact on NH_3 emissions. However, there do not appear any studies that investigate the influence of the slurry depth on NH_3 emission from stored pig slurry both under laboratory and field conditions. This is likely because the change of slurry depth affect the quantity and quality of slurry in the storage tank; it does not alter the surface area of the slurry. The rate of NH_3 release from slurry is proportional to the slurry surface area (Ni et al., 1999b). Thus, it is reasonable to assume that the higher amount of slurry due to higher pig density that needs to be stored in the slurry tank outside of the pig house would not affect the rate of NH_3 emissions. However, if the change in regulation results in more pigs and slurry per production site, there could in principle be a risk of exceeding the slurry storage capacity during times when spreading is undesirable and/or prohibited. If supplementary slurry tanks need to be installed as a result of this, then higher total NH_3 emissions from the slurry storage tanks will occur.

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Review of ammonia emissions from a pig house slurry pit and outside storage

The main objective of this report was to review and gather scientific information and data from the literature to test the assumption that the NH3 emission from a pig house slurry pit and outside storage is more dependent on the area of slurry surface than on the produced quantity or slurry (with the same ammoniacal nitrogen concentration) in the existing slurry-based livestock systems.

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