Emissions of ammonia, nitrous oxide and methane from pig houses: Influencing factors and mitigation techniques

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1. Introduction

Pork is currently the most widely consumed meat product in the world, accounting for 38% of total meat consumption. By 2050, worldwide pig consumption is expected to increase by 40% owing to the demographic growth, the changes in food preferences and the agricultural intensification (FAO, 2011). The impact of livestock production on the environment is attracting increasing attention, especially the effects on pollutant gases like ammonia and greenhouse gas emissions, i.e. carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Globally, livestock production accounts for 64% of ammonia emissions and 18% of anthropogenic emissions of cumulated greenhouse gases (FAO, 2006). Pig sector contribute to about 15% of livestock related emissions (Olivier et al., 1998; FAO, 2006 and 2011).

The aim of this paper is to describe the factors that impact NH_3, N_2O and CH_4 emissions from pig buildings and to identify some mitigation techniques regarding housing conditions. The effects of feeding strategies will not be addressed in this work whereas they constitute interesting options for reduction.

2. Sources of ammonia, nitrous oxide and methane from pig houses

The main source of NH_3 is the rapid hydrolysis of urea of urine by the urease leading to ammonium (NH_4^+) (Cortus et al., 2008). Another source of NH_3 is the degradation of undigested proteins, but this pathway is slow and of secondary importance (Zeeman, 1991). The urease is a cytoplasmic enzyme largely present in faecal bacteria (Mobley and Hausinger, 1989). In livestock buildings, it is present in abundance on fouled surfaces like floors, pits and walls (Ni et al., 1999). Urease activity is affected by temperature with low activity below 5–10°C and above 60°C (Sommer et al., 2006). Under practical conditions, models show an exponential increase of urease activity related to temperature (Braam et al., 1997). Urease activity is also affected by pH with optimum ranging from 6 to 9, while animal manure pH is usually buffered to between 7.0 and 8.4. Therefore, optimal conditions for complete urea hydrolysis are largely met in animal husbandry, making the urea availability the limiting factor. The NH_4^+ production depends also on manure moisture content because water is necessary for bacterial activity (Groot Koerkamp, 1994). Thus, NH_4^+ production is optimal between 40% and 60% moisture content but releases decrease at values above and below this range. Ammonia production stops below 5–10% moisture content (Elliot and Collins, 1983).

The formation of N_2O occurs during incomplete nitrification/denitrification processes that normally convert NH_3 into non-polluting N_2. During nitrification, N_2O can be synthesized where there is a lack of oxygen and/or a nitrite accumulation. During denitrification, N_2O is synthesized in the presence of oxygen and/or low availability of degradable carbohydrates (Poth and Focht, 1985; Driemer and Van den Weghe, 1997). In addition, N_2O can be formed during other microbial pathways: aerobic or anaerobic ammonium oxidation (so-called nitrifier denitrification and anamox, respectively). Most of nitrifying and denitrifying microorganisms are not thermophilic and thus the N_2O formation is inhibited by temperature above 40-50°C. Finally, N_2O can be produced during an abiotic ammonium conversion under acidic conditions (so-called chemodenitrification) (Oenema et al., 2005; Petersen et al., 2006). The relative contribution of these various pathways has to be still determined. Anyway, N_2O synthesis needs close combination of aerobic and anaerobic areas. These heterogeneous conditions are not met within slurry but litter. However, N_2O emissions can occur from slurry when a dry crust is formed on the surface with combination of anaerobic and aerobic micro-sites. Because of these numerous sources and environmental controls, N_2O production from manure has a highly stochastic nature, especially with litter systems.

Methane production is slightly less complex. It originates from the anaerobic degradation of organic matter performed by mesophilic/thermophilic bacteria with an optimal pH close to neutrality (Hellmann et al., 1997; El-Mashad et al., 2004). In piggery, the sources of CH_4-emissions are the animal digestive tract and the releases from the waste. The level of enteric CH_4 is function of the fermentative capacity of the hindgut and the content, source and solubility of dietary fibre (Philippe et al., 2008). In manure, CH_4-release is promoted by high temperature, high organic matter content and anaerobic conditions (Amon et al., 2006). On contrary, the production is inhibited under aerobic conditions or high concentration of ammonium and sulphides (Monteny et al., 2006). If a surface crust is formed on slurry, CH_4 produced within the manure can be oxidized into CO2 during passage through the crust with less CH_4 releases as consequence (Petersen et al., 2006).

3. Influencing factors

3.1. Climatic conditions

Emissions of pollutant gases are positively related to ambient temperature and ventilation rate thanks to effects on physical, chemical and microbiological processes. For example, when ambient temperature increased from 17 to 28°C, NH_3 emissions increased from 12.8 to 14.6 g NH_3/pig.day (Granier et al., 1996). When ventilation rate increased from 9.3 to 25.7 m^3/h.pig, NH_3 emissions increased by 25% (Granier et al., 1996). However, it is important to notice that temperature and ventilation are interlinked as seen elevate flow decreases air temperature. The ventilation type and the location of the fans also contribute to modulate the emissions. Air inlets or outlets located near the manure surface increase the emissions consequently to higher air exchange rate at interface (Hayes et al.,2006). Nevertheless, the ambient parameters must primarily respect the bioclimatic comfort of the animals. Moreover, the climatic conditions may alter the pig behavior with indirect effects on emissions. Thus, the control of ambient parameters especially under hot conditions, has to encourage the pigs to foul the excretory area and to remain clean and dry the lying and exercise areas (see below).

3.2. Floor type, pen design and manure management

In pig production, the main housing systems are based on slatted floor or bedded floor. Within both floor types, a large range of techniques were developed in order to reduce the environmental impact of pig production.

3.2.1. Slatted floor systems

Most of the pigs are kept on concrete slatted floors with a deep pit underneath for the storage of the slurry for long periods (several months). This so-called “deep-pit” system is usually considered as reference technique.

Good drainage of manure through the slatted floor limits fouled areas that are significant sources of NH_3 (Svennerstedt, 1999). Drainage properties of the floor are influenced by material characteristics, slat design and width of openings. Concrete characteristics, such as roughness and porosity, impact NH_3 production, with lower NH_3 emissions with smooth floors (Braam and Swierstra, 1999). In the same way, substituting concrete slats by cast iron, metal or plastic slats can reduce NH_3 production by 10 to 40 % (Pedersen and Ravn, 2008). The profile of the slats has to be designed in order to avoid manure lodging between slats. Thus, trapezoidal cross section favours manure drainage, with better results from protruding (Svennerstedt, 1999) or sharp edges (Ye et al., 2007; Hamelin et al., 2010). Increasing opening size is also a good means of facilitating drainage and limiting NH_3 production. Under laboratory conditions, enlarging gap widths, from 2 to 30 mm, decreases emission by more than 50% (Svennerstedt, 1999). Besides traditional rectangular openings, round or semi-circular openings may be used, but with increased risk of clogging, greater fouled area and greater emissions (Svennerstedt, 1999). The effects of slat characteristics on N_2O and CH_4-emissions were very few studied. However, it can be assumed that they are of little importance, considering the formation process of these gases.

Reducing the emitting slurry surface is commonly used to decrease the emissions. Thus, partly slatted floor systems with reduced slurry pit area is known to produce lower levels of NH_3 compared to fully slatted floor systems, as confirmed by numerous studies. For example, in the experiments of Sun et al. (2008) with fattening pigs, NH_3 emission factors are reduced by about 40% by replacing fully slatted floors by partially slatted floors (37% of pen floor area). Decreasing slatted floor area from 50% to 25% of total area shifts daily emissions from 6.4 to 5.7 g NH_3 per fattening pig (Aarnink et al., 1996). On the contrary, some authors reported similar emissions whatever the proportion of slatted floor (Guingand and Granier, 2001; Philippe et al., 2012a). By reducing the slatted floor by 50%, Philippe et al. (2012a) did not measured significant difference for NH_3, N_2O and CH_4 emissions. Moreover, higher emissions have been observed for gestating sows on partly slatted floor with NH_3, N_2O and CH_4 emissions increased by 24, 11 and 17%, respectively (Philippe et al., 2010a). According to Guingand and Granier (2001), NH_3 emissions during summer time were increased by about 80% with partially slatted floor (50% of pen floor area). Actually, the excretory behaviour of the pigs that tend to foul the solid area under specific conditions like hot temperature or high animal density fails to reduce emissions with partly slatted floor. The installation of a sprinkler to cool the animals or sufficient available space area could prevent increasing of emissions. Moreover, designing housing conditions that respect the natural excretory/lying behaviour of the pig may contributes to limited emissions. Most of the pigs urinate and defecate in the free corner of the pen, away from the feeder or drinker (Aarnink et al., 1996), indicating where the slats have to be placed. The pen partition type also impacts on the dunging location. Closed pen partitions reduce air drafts, keep the sleeping area warmer and maintain a temperature gradient between the warmer lying area and the cooler dunging area. With open pen partitions, pigs are inclined to urinate and defecate in the boundary area (Hacker et al., 1994). The slat material can influence the excretory behaviour of the pigs. For example, in a partially slatted pen, a metal slatted floor with triangular section and metal studs was especially developed to create a fixed dunging place, by preventing the pigs from lying in the area with studs (Aarnink et al., 1997).

Reducing the emitting manure surface can also be achieved by modification of the pit design, principally thanks to sloped pit walls or manure gutters. Doorn et al. (2002) reported a reduction of NH_3 emissions by 28% for fattening pigs while the emitting surface was also reduced by 28%. Similar results were observed with weaned piglets (van Zeeland and den Brok, 1998) and gestating sows (Timmerman et al., 2003).

Frequent manure removal can also be proposed as a mean to diminish the emissions from the building. Total emissions including storage will be reduced provided lower outside temperature than inside or specific manure treatments. A fortnightly removal reduced NH_3 emissions by 20% compared to a system where the slurry was stored for the duration of the finishing period (Guingand, 2000). A weekly discharge reduced NH_3 as well as N_2O and CH_4 emissions by about 10% compared to the traditional deep-pit system (Osada et al., 1998). With the same removal strategy, Guarino et al. (2003) observed NH_3 and CH_4 emissions reduced by 38 and 19%, respectively, but N_2O emissions were doubled.

Pit flushing is also an efficient mean to reduce emissions. Significant reduction by 45% for NH_3 and 49% for CH_4 were observed with this technique compared to static pits (Lim et al;, 2004; Sommer et al., 2004). In association with manure gutters or flushing tube incorporated into the concrete slat, Lagadec et al. (2012) measured NH_3 and N_2O emissions reduced by 5 to 20%. Frequency, duration and pressure of the flushing water also impacted on the efficiency of mitigations (Kroodsma et al., 1993; Misselbrook et al., 2006). For example, frequent flushing (every 1-2 h) for short periods (2 seconds) is more effective than prolonged (3-6 seconds) but less frequent flushing (every 3.5 h) (Kroodsma et al., 1993). The use of fresh water, as opposed to recycled water, further reduces emissions. This is especially the case for CH_4 because methanogenesis is rapidly initiated in the channel if small part of slurry remains in the pit after emptying whereas, without inoculums in the pit, CH_4 formation is low and initiated after few days (Sommer et al., 2007).

The manure can also be removed by scraping. Standard flat scraper systems consist of a shallow slurry pit with a horizontal steel scraper under the slatted floor, allowing the manure to be removed from the building several times a day (Groensetein, 1994). However, this type of manure removal seems to have no positive effect on NH_3 emissions (Predicala et al., 2007; Kim et al., 2008a; Lagadec et al., 2012). Indeed, the surface under the slat is always soiled because the scraping spreads faeces and urine over the pit and the small film left on it creates a greater emitting area.

In contrast, the V-shaped scraper system is effective in reducing emissions since it is associated with separation of urine from faeces. This system involves a channel with two inclined surfaces on each side of a central gutter. Thanks to a longitudinal slope of around 1%, the liquid fraction continuously runs off by gravity towards the gutter before being redirected outside the building. The solid fraction remains on the inclined surface before being scraped several times a day (Godbout et al., 2006). By the installation of an under-slat V-shaped scraper, reductions around 40-50% were achieved for NH_3 and N_2O, and around 20% for CH_4 (Godbout et al., 2006; Lagadec et al., 2012). Conveyor belts are also an effective system to separate urine from faeces under slats. They are composed of a perforated belt through which the liquid percolates into a conventional pit whereas the faeces left on the belt are conveyed out of the pen into a separate collection pit (Lachance et al., 2005; Pouliot et al., 2006). With this system, authors reported reductions of NH_3- and CH_4-emissions around 50% and 20%, respectively, in comparison with conventional storage systems (van Kempen et al., 2003; Godbout et al., 2006). These techniques seem also advantageous because the separation facilitates recycling and treatment of manure, reduces storage requirements and transportation costs, and offers more homogenous materials for land spreading.

3.2.2. Bedded systems

For the past few decades, bedded systems have met renewed interest, as they are related to improved welfare, reduced odour nuisance and a better brand image of livestock production. However, this technique is associated with increased cost principally due to the straw use and the labour for litter management even if building costs are usually reduced (Philippe et al., 2006). For existing buildings, this system can be quite easily applied for housing with concrete solid floor.

Comparisons between bedded systems and traditional slatted floor systems show contradictory results regarding NH_3 and CH_4 emissions while N_2O emissions were systematically increased with the former but presenting large variation between studies (Philippe et al., 2007a, 2007b and 2011). These discrepancies can be explained by the wide range of rearing techniques of pigs on litter: the litter substrate, the amount of supplied litter, the space allowance and the litter management. These parameters influence the physical structure (density, humidity) and the chemical properties of the litter that interact to modulate gas emission levels (Dewes, 1996; Groenestein and Van Faassen, 1996; Misselbrook and Powell, 2005).

Several bedding materials were tested in regards to emissions. The most frequent substrates are straw and sawdust. Compared to straw litters, sawdust litters produce less NH_3 and CH_4 but more N_2O (Nicks et al., 2003 and 2004; Cabaraux et al., 2009). By instance, the raising of five successive batches of weaned piglets on the same sawdust litter, reduced the NH_3 emissions by 62% (0.46 vs. 1.21 g NH_3/pig.day) and the CH_4 emissions by 49% (0.77 vs. 1.58 g CH_4/pig.day), but 4-fold N_2O emissions (1.39 vs. 0.36 g N_2O/pig.day), compared to straw litter (Nicks et al., 2004). Higher manure density observed with sawdust may impair composting process, which normally increases the manure temperature and air exchange through it. Consequently, NH_3 emissions are reduced, which increases the amount of ammonium available for non-thermopilic nitrifying bacteria, with higher N_2O emissions as consequence (Sommer, 2001; Hansen et al., 2006). Moreover, lower temperatures inside the litter diminish the CH_4 production that is very sensitive to temperature (Hansen et al., 2006). Indeed, Husted (1994) found that emissions of CH_4 from dung heaps can be divided by factor from 2.7 to 10.3 when heap temperatures were decreased by 10°C.

Increasing the amount of substrate also impacts emissions with typically reduction in NH_3 and N_2O productions but variable effects on CH_4 production (Yamulki et al., 2006; Rigolot et al., 2010; Philippe et al., preliminary results). The addition of litter materials increases the C/N ratio and the aeration of the manure, which favour the bacterial growth and the N assimilation into stable microbial protein resulting in lower NH_3 and N_2O emissions (Dewes, 1996; Sommer and Moller, 2000). Regarding CH_4, substrate supply may inhibit production because of greater aeration on one hand, but may promote emissions by providing degradable carbohydrates for methanogenic bacteria on the other hand (Yamulki, 2006).

Some research addressed the effect of the surface of the bedded area on emissions. Contradictory results were obtained whatever the gas studied, NH_3, N_2O or CH_4 (Hassouna et al., 2005; Rigolot et al., 2010; Philippe et al., 2010b and in press). This indicates that emissions from litter greatly depends of particular conditions inside the manure (C/N ratio, aeration, temperature) rather than just space allowance

With deep litter systems, NH_3-, N_2O- and CH_4-emissions increase regularly in the course of time, principally thanks to accumulation of dejection and compaction (Philippe et al., 2007a, 2010b, 2012b). Therefore, like for slurry systems, frequent manure removal was proposed to reduce these pollutant emissions. In this way, straw flow systems have been developed combining regular straw supply, sloped floor and frequent manure scraping (Bruce, 1990). This kind of manure management is efficient to reduce N_2O and CH_4 emissions but increases NH_3 emissions (Amon et al., 2007, Philippe et al., 2007b; Philippe et al., 2012b). While the aeration of the manure during the scraping and removal inhibits the production of N_2O and CH_4, this technique fails to reduce NH_3 emissions because spreading of faeces and urine over the floor enhances NH_3 synthesis in place of promoting microbial N assimilation. As it is for the slurry, reduction of total emissions can be achieved provided lower outside temperature during storage than inside or specific manure treatments.

Several pen designs were elaborated to stimulate the separation of the excretory and lying behaviours, and thus to limit pollutant emissions. Some strategies associate bedded floor with slatted floor and/or solid floor. Jeppsson (1998) tested fattening pen composed of a bedded area at the front of the pen for feeding and resting (0.90 m^2/pig) and a slatted floor area at the back of the pen for dunging (0.25 m^2/pig). With straw-based litters, emissions were around 20-25 g NH_3/pig.day. These quite high emissions were partly explained by the clogging of the slatted floor with bedding material. A pen design with a sloped concrete floor as feeding and lying area (0.84 m^2/pig), and a deep litter as excreting area (0.54 m^2/pig) resulted in lower emissions, with on average 8.3 g NH_3/pig.day (Kaiser and Van den Weghe; 1997). A model was developed by Groenestein et al. (2007) to predict the NH_3 emissions from a litter system for group-housed sows combining straw bedded area, concrete floor and slatted floor. The model showed that increased urination frequency in the straw bedding rather than on the other floor types lowered the emissions. Therefore, pen designing should be aimed at decreasing excretory behaviour on solid and slatted floors and allowing more excretion on litter.

4. Conclusion

Several mitigation techniques are available to reduce NH_3-, N_2O- and CH_4-emissions from pig houses, whatever the floor type. However, some strategies show contradictory effects depending on the circumstances and the gas. By example with slatted systems, reducing the emitting surface by implementing a partly slatted floor is efficient to decrease the emissions on condition that attention is paid to prevent the soiling of the solid part of the floor. With bedded systems, the use of sawdust in place of straw reduces the emissions of NH_3 and CH_4 but increases the emissions of N_2O. Anyway, solid manures produce significantly more N_2O than slurry, which constitutes the main inconvenient of bedded systems. Since pollutant emissions also occur during storage, treatment and spreading of manure, complete evaluation of the entire manure management process is needed to really limit global emissions. Some options should prevent potential reduction in a next step or constitute opportunities to further diminish the emissions. In addition, the choice for a housing system is also guided by other factors, such as animal health, performance and welfare, agronomical values of manure and surely the investment and operating costs. Specific field conditions will guide decision in favour of mitigation techniques.

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