ACADEMIE UNIVERSITAIRE WALLONIE-EUROPE
UNIVERSITE DE LIEGE
FACULTE DE MEDECINE VETERINAIRE
DEPARTEMENT DES PRODUCTIONS ANIMALES
SERVICE D'ECOLOGIE VETERINAIRE

EMISSIONS D'AMMONIAC ET DE GAZ A EFFET DE SERRE ASSOCIEES A L'HEBERGEMENT DE PORCS CHARCUTIERS ET DE TRUIES GESTANTES SUR CAILLEBOTIS ET SUR LITIERE PAILLEE

AMMONIA AND GREENHOUSE GAS EMISSIONS ASSOCIATED WITH THE REARING OF FATTENING PIGS AND GESTATING SOWS ON SLATTED FLOOR AND STRAW-BASED LITTER

François-Xavier PHILIPPE

THESE PRESENTEE EN VUE DE L'OBTENTION DU GRADE DE DOCTEUR EN SCIENCES VETERINAIRES

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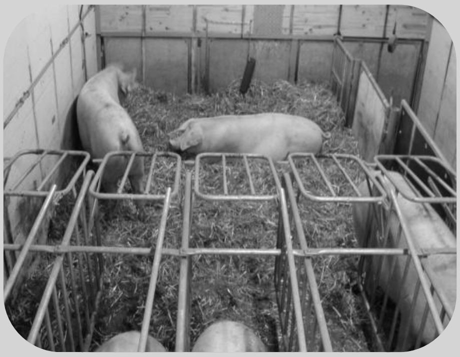

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A mes trois petits cochons, Gaston, Martin et Hadrien,

« Le porc est un animal docile qui obéit à son maître et le protège contre les bêtes de la forêt. Avec ses boutoirs, il repousse vaillamment des animaux plus forts que lui. Chaque jour, il se contente de la nourriture qu'il trouve dans le sol, mais, comme le chien, ne refuse jamais ce qu'on lui donne. Il est de tempérament chaud et plein d'ardeur ; son ouïe est plus fine que celle de l'homme […]. La femelle met bas de nombreux enfants dont elle s'occupe dès la naissance. C'est une mère attentionnée : quand il y a plus de porcelets que de mamelles, elle partage son repas avec ceux qui n'ont rien. »

Liber de naturis rerum,
compilation encyclopédique latine du XIIème siècle

« Le porc est une bête immonde qui fouille constamment la terre de son groin pour y chercher sa nourriture. Il regarde toujours vers le sol et ne lève jamais la tête vers le Seigneur. C'est pourquoi il est l'image de l'homme pécheur qui préfère les biens de ce monde aux trésors du Ciel. Bien qu'il ait l'ouïe fine, le verrat n'entend pas la parole de Dieu mais préfère écouter les appels incessants de son ventre. Ils symbolisent les puissants qui ne travaillent pas et ne sont jamais rassasiés de plaisirs. La truie est une femelle lascive […] ; ses porcelets sont plus nombreux que ses mamelles. Elle mange souvent des ordures ou des charognes et parfois même se plaît à dévorer la chair de ses propres enfants. »

Liber animalium,
bestiaire latin du XIIème siècle

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Resume

Les impacts environnementaux des activités d'élevage sont l'objet d'une attention croissante. Le secteur contribue de manière significative à l'émission de gaz polluants comme l'ammoniac (NH_3) et les gaz à effet de serre (GES). L'ammoniac contribue à la formation de particules fines ainsi qu'à l'eutrophisation et l'acidification des écosystèmes. Les gaz à effet de serre, regroupant le dioxyde de carbone (CO_2), le méthane (CH_4) et le protoxyde d'azote (N_2O), participent au phénomène de changement climatique et de réchauffement planétaire. Le porc est actuellement la viande la plus consommée au monde, et une augmentation de sa production est prévue dans les années à venir en raison de la croissance démographique, de l'évolution des préférences alimentaires et de l'intensification de l'agriculture. L'évaluation environnementale des systèmes de production porcin devient nécessaire afin d'assurer la durabilité de la filière. Cette étude a donc pour objectif de comparer différents modes d'hébergement pour porcs charcutiers et truies gestantes quant à leurs émissions de NH_3 et de GES à partir des bâtiments, de déterminer des facteurs d'influence et d'identifier des moyens potentiels de réduction.

Cette étude est composée de six essais traitant des thématiques suivantes :

- Comparaison entre les système à caillebotis et à litière de paille accumulée pour des porcs charcutiers (5 bandes successives) ;
- Comparaison entre les système à caillebotis et à litière de paille accumulée pour des truies gestantes (3 bandes successives);
- Effets de la surface disponible sur les émissions gazeuses associées à l'élevage de truies gestantes sur litière de paille accumulée (4 bandes successives) ;
- Effets de la quantité de paille sur les émissions gazeuses associées à l'élevage de porcs charcutiers sur litière de paille accumulée (3 bandes successives) ;
- Comparaison entre les systèmes de litière de paille accumulée et de litière glissante pour des porcs charcutiers (3 bandes successives) ;
- Influence de l'accès permanent à une zone d'alimentation bétonnée sur les émissions gazeuses associées à l'élevage de truies gestantes sur litière de paille accumulée (3 bandes successives).

Les essais se sont déroulés dans les installations de l'Université de Liège (Belgique). Des groupe de 10 ou 16 porcs charcutiers et de 5 truies gestantes ont été hébergés dans des locaux séparés (un groupe par local). Selon l'essai, deux ou trois locaux identiques en volume, en superficie et en équipement de ventilation étaient utilisés et aménagés en fonction des conditions de logement testées. La ventilation était contrôlée et s'adaptait automatiquement en fonction de la température ambiante. Les émissions gazeuses ont été mesurées par détection photo-acoustique infrarouge durant 3 ou 4 séries de mesure de 6 jours consécutifs réparties de manière homogène sur l'ensemble des périodes d'engraissement et de gestation. Pour l'analyse statistique, les données ont été testées par un modèle mixte pour données répétées (proc MIXED).

Comparé à l'élevage de porcs charcutiers sur caillebotis, l'élevage sur litière accumulée est associé à une augmentation des émissions de NH_3 et de N_2O qui sont plus que doublées (13,1 *versus* 6,2 g NH_3 porc^{-1} jour^{-1}, P<0,001 ; 1,11 vs 0,5 g N_2O porc^{-1} jour^{-1}, P<0,001) ; les émissions de CH_4 n'ont pas été significativement différentes (environ 16 g CH_4 porc^{-1} jour^{-1}, P>0,05).
La comparaison de ces deux systèmes d'hébergement, caillebotis et litière accumulée, destinés à des truies gestantes confirme une émission de N_2O plus élevée (presque quintuplée), à partir des litières accumulées comparativement à celle en provenance des lisiers (2,27 *versus* 0,47 g N_2O truie^{-1} jour^{-1}, P<0,001). En revanche, tant les émissions de NH_3 que de CH_4 à partir des litières ont été moins élevées que celles des lisiers, avec une réduction de l'ordre de 30 % pour le NH_3 (12,8 *versus* 9,1 g NH_3 truie^{-1} jour^{-1}, P<0,001) et de 9% pour le CH_4 (9.2 *versus* 10.1 g CH_4 truie^{-1} jour^{-1}, P<0.001).
Les différences observées en fonction de la catégorie d'animaux pourraient être attribuées aux variabilités dans l'espace mis à la disposition des animaux et aux quantités de paille utilisées pour les litières.
Réduire la superficie paillée mise à disposition de truies gestantes élevées en groupe en passant de 3,0 à 2,5 m^2 par truie permet de réduire les émissions de NH_3 de 14 % (6,5 *versus 7*,6 g NH_3 porc^{-1} jour^{-1}, P<0,01).
Une réduction plus importante de la superficie paillée (1,8 m^2 par truie) compensée par la mise à disposition d'une surface bétonnée non paillée (1,2 m^2 par truie) n'aboutit pas à une réduction supplémentaire des émissions de NH_3, vraisemblablement parce qu'une partie des déjections est déposée sur la surface bétonnée. Avec ce système, on observe une réduction de moitié des émissions de N_2O (3,1 *versus* 6,1 g N_2O truie^{-1} jour^{-1},

P<0,001) et une augmentation de près de 30 % des émissions de CH_4 (12,8 *versus* 9,9 g CH_4 truie^{-1} jour^{-1}, P<0,001), probablement en raison d'un tassement plus important de la litière, en comparaison au système entièrement paillé.

L'augmentation de 50 à 100 kg par porc charcutier de la quantité de paille utilisée pour une période d'engraissement a eu pour conséquence une réduction des émissions de NH_3 de 11 % (16,0 *versus* 18,0 g NH_3 porc^{-1} jour^{-1}, P<0,01) et de N_2O de 36 % (0,7 *versus* 1,1 g N_2O porc^{-1} jour^{-1}, P<0,001). En revanche, les émissions de CH_4 ont été presque doublées (9,1 *versus* 4,8 g CH_4 porc^{-1} jour^{-1}, P<0,001), ce qui pourrait être attribué à une température plus élevée au sein des fumiers plus riches en paille.

Pour l'hébergement de porcs charcutiers, le recours à la technique dite de la litière glissante qui évite l'accumulation progressive du fumier sous les animaux réduit de près de moitié les émissions de CH_4 (8,9 *versus* 16,5 g CH_4 porc^{-1} jour^{-1}, P<0,001) et de N_2O (0,68 *versus* 1,50 g N_2O porc^{-1} jour^{-1}, P<0,001) mais est associée à une augmentation des émissions de NH_3 de 10 % (13,3 *versus* 12,1 g NH_3 porc^{-1} jour^{-1}, P<0,05).

La production de CO_2 mesurée lors de ces essais a varié de 1,7 à 2,5 kg CO_2 porc^{-1} jour^{-1} avec les porcs charcutiers et de 2,1 à 3,1 kg CO_2 truie^{-1} jour^{-1} avec les truies gestantes. Les émissions de CO_2 ont pour source principale la respiration des animaux qui dépend de leur métabolisme. La contribution des effluents a été estimée à environ 10 et 30% des émissions totales respectivement pour les lisiers et les fumiers. La production plus élevée à partir des fumiers est probablement due au processus de compostage s'u opérant de manière aérobie.

En conclusion, les comparaisons effectuées entre modes de logement n'ont pas permis de mettre en évidence un système réduisant l'émission de l'ensemble des gaz mesurés. Si le recours à l'élevage sur litière offre parfois un avantage en termes de réduction des émissions de NH_3 et de CH_4, il est associé à de plus fortes émissions deN_2O et de CO_2. Tout choix d'un système d'hébergement doit cependant aussi prendre en compte d'autres aspects que les niveaux d'émissions gazeuses dont notamment l'effet sur l'état de santé, le bien-être et les performances des animaux. A propos des performances, nos études ont montré qu'elles sont de niveaux équivalents lors de l'élevage sur litière et sur caillebotis. Enfin, le choix d'un système d'hébergement se fera aussi en tenant compte de l'investissement requis, des frais de fonctionnement et de la charge de travail qui y sont associés.

ABSTRACT

The impact of livestock production on the environment is attracting increasing attention. It significantly contributes to polluting gas emissions like ammonia (NH_3) and greenhouse gases (GHG). Ammonia is implicated in particulate matter formation and contributes to eutrophication and acidification of ecosystems. Greenhouse gases, including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), participate in global warming and climate change. Pork is currently the most widely consumed meat product in the world, and its production is expected to increase in the coming years owing to the demographic growth, the changes in food preferences and the agricultural intensification. Environmental assessment of pig production systems becomes essential to ensure the sustainability of the sector. Thus, the aims of this study are to compare several rearing systems for fattening pigs and gestating sows as regards to their impact on NH_3-and GHG-emissions from buildings, to specify influencing factors and to point out potential mitigations techniques.

This study is divided into six trials dealing with:

- Comparison between slatted floor and straw-based deep litter systems for fattening pigs (5 replicates);
- Comparison between slatted floor and straw-based deep litter systems for gestating sows (3 replicates);
- Effects of available surface area on gas emissions associated with gestating sows kept on straw-based deep litter (4 replicates);
- Effects of the amount of straw on gas emissions associated with fattening pigs kept on deep litter (3 replicates);
- Comparison between straw-based deep litter and straw flow systems for fattening pigs (3 replicates);
- Influence of permanent use of feeding stalls on concrete floor as living area on gas emissions for gestating sows kept on straw deep-litter (3 replicates).

The trials were carried out in the installations of Liège University (Belgium). Groups of 10 or 16 fattening pigs and 5 gestating sows were used for this study. Groups were housed in separated rooms (1 group per room). Depending of the trial, two or three

rooms were arranged and fitted as function of the rearing system. Rooms were identical regarding their surface, volume and ventilation system. Ventilation was automatically adapted to maintain a constant ambient temperature. The gas emissions were measured by infra red photoacoustic detection during 3 or 4 series of continuous measurement of 6 consecutive days homogeneously distributed throughout the fattening or gestating periods. For statistical analyses, data were tested in the form of a mixed model for repeated measurements (proc MIXED).

Compared with the slatted floor system, the bedded floor system for fattening pigs is associated with twofold NH_3- and N_2O-emissions (13.1 *versus* 6.2 g NH_3 pig^{-1} day^{-1}, $P<0.001$; 0.54 *versus* 1.11 g N_2O pig^{-1} day^{-1}) whereas CH_4 emissions seem not significantly affected by the floor type (around 16 g CH_4 pig^{-1} day^{-1}, $P>0.05$).
The comparison between the two systems for gestating sows confirms higher N_2O emissions (nearly fivefold) from litters rather than slurries (2.27 *versus* 0.47 g N_2O sow^{-1} day^{-1}). However, both NH_3 and CH_4 emissions were lower from litters, with reduction by 30% for NH_3 (12.8 *versus* 9.1 g NH_3 sow^{-1} day^{-1}, $P<0.001$) and by 9% for CH_4 (9.2 *versus* 10.1 g CH_4 sow^{-1} day^{-1}, $P<0.001$).
Discrepancy with respect to the animal type could be explained by differences in space allowance and in amount of supplied straw.
Reducing the available bedded area for group-housed gestating sows from 3.0 to 2.5 m^2 per animal leads to decreased NH_3 emissions (6.5 *versus* 7.6 g NH_3 pig^{-1} day^{-1}, $P<0.01$).
Further reduction of bedded area (1.8 m^2 per sow) compensated by an access to a concrete floor area (1.2 m^2 per sow) does not result in lower NH_3 emissions, probably due to the soiling of the concrete floor. With this system, N_2O emissions are reduced by half (3.1 *versus* 6.1 g N_2O sow^{-1} day^{-1}, $P<0.001$) and CH_4 emissions are increased by nearly 30% (12.8 *versus* 9.9 g CH_4 sow^{-1} day^{-1}, P<0..001), probably due to higher compaction of the manure, compared with deep litter system.
Increasing the amount of straw from 50 to 100 kg per fattening pig results in reductions in NH_3 emissions by 11% (16.0 *versus* 18.0 g NH_3 pig^{-1} day^{-1}, $P<0.01$) and N_2O emissions by 36% (0.7 *versus* 1.1 g N_2O pig^{-1} day^{-1}, $P<0.001$) but CH_4 emissions are nearly twofold with the larger straw supply (9.1 *versus* 4.8 g CH_4 pig^{-1} day^{-1}, $P<0.001$). It could be linked to higher litter temperature in case of generous straw bedding.
Compared with deep litter, the straw flow system for fattening pigs prevents manure accumulation under the animals, with reductions in CH_4 emissions (8.9 *versus* 16.5 g

CH_4 pig^{-1} day^{-1}, P<0.001) and N_2O emissions (0.68 *versus* 1.50 g N_2O pig^{-1} day^{-1}, P<0.001) as consequences. However, NH_3 emissions are increased by 10% (13.3 *versus* 12.1 g NH_3 pig^{-1} day^{-1}, P<0.05).

In these experiments, CO_2 production ranged from 1.7 to 2.5 kg CO_2 pig^{-1} day^{-1} with fattening pigs and from 2.1 to 3.1 kg CO_2 sow^{-1} day^{-1} with gestating sows. Emissions of CO_2 mainly originate from the pigs respiration that depends on animal metabolism. Manure contribution was estimated to about 10 and 30% of total emissions with slurry- and litter-based systems respectively. Higher production from litter was probably due to aerobic composting process.

In conclusion, according to the comparisons carried out in this study, none of the rearing systems is associated with concurrent reductions in NH_3, N_2O, CH_4 and CO_2 emissions. In some cases, litter systems may present reduced NH_3 and CH_4 emissions, but systematically increased emissions of N_2O and CO_2. Apart from environmental consideration, the choice for a rearing system will be guided by specific field conditions taking into account the effects on health, welfare and performance of animals. In this study, production performance was unaffected by the floor type. Finally, decision in favor of a housing system has to integrate concerns about investments, operating costs and workload.

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Introduction

1. Contexte general et objectifs de l'etude

Les attentes sociétales liées à l'élevage sont actuellement multiples et grandissantes. Outre son rôle initial de pourvoyeur de nourriture, il est au centre d'enjeux importants en termes économiques, sociaux, sanitaires et de bien-être animal. Les exigences d'ordre environnemental s'y sont ajoutées au fur et à mesure que les atteintes à la qualité des eaux, des sols et de l'air sont devenues évidentes et quantifiables.

Un rapport de la FAO (Steinfeld et al., 2006) affirme que l'élevage contribue fortement aux problèmes environnementaux les plus pressants de la planète, à savoir la dégradation des terres (déforestation, surpâturage), le réchauffement climatique (gaz à effet de serre), la pollution de l'atmosphère (gaz acidifiants, particules fines, bio-aérosols), l'altération des ressource en eau (qualité et quantité), la pollution des sols (métaux, toxiques, pesticides, résidus médicamenteux, agents pathogènes) et la perte de biodiversité (pression sur les habitats naturels). A cela s'ajoute des perturbations aux niveaux local (odeurs, bruits) et global (consommation d'énergie et diminution des ressources fossiles). A l'avenir, la croissance de la population mondiale associée à l'évolution des préférences alimentaires vont favoriser l'augmentation de la demande globale en protéines animales. L'intensification, la spécialisation et la concentration des élevages accentueront encore davantage la pression environnementale sur certaines régions du monde. La filière porcine, sujette à une certaine industrialisation de la production, est particulièrement concernée par ces problématiques. Le porc est actuellement la viande la plus consommée au monde et on prévoit une augmentation de sa production d'environ 40% d'ici à 2050 (FAO, 2011).

L'accélération des dégradations et la sensibilisation croissante des populations ont incité les dirigeants à concevoir des réglementations nationales et internationales visant à limiter les impacts environnementaux de l'élevage. La directive Nitrates (Directive 91/676/CEE) vise à protéger les eaux contre la pollution par les nitrates d'origine agricole (effluents d'élevage et engrais minéraux). La désignation de zones vulnérables et des contraintes sur le stockage et l'épandage des effluents sont concernés par cette mesure. La directive IPPC (Integrated Pollution Prevention and Control, Directive 96/61/CE) impose l'application des meilleures techniques disponibles afin de prévenir et réduire les pollutions émises par les installations jugées les plus polluantes. En productions animales, sont concernés les élevages de porcs de plus de 2 000 places d'engraissement ou de plus de 750 emplacements de truies, ainsi que les ateliers avicoles de plus de 40 000 emplacements. Le protocole de Kyoto (1997) a pour objectif de maîtriser les changements climatiques par la réduction des émissions de gaz à effet de serre Le protocole de Göteborg (1999) et la directive NEC (National Emission Ceiling, Directive 2001/81/CE) cible la réduction des pollutions atmosphériques impliquées dans l'acidification, l'eutrophisation et la formation d'ozone troposphérique. La législation fixe des plafonds d'émissions par état. Les gaz concernés sont le dioxyde de soufre, les oxydes d'azote, les composés volatils organiques et l'ammoniac.

L'application de ces législations implique de connaître les niveaux d'émissions associés aux différentes pratiques d'élevage et d'identifier des moyens de réduction efficaces applicables sur le terrain. Conscients des enjeux sociétaux dont ils sont l'objet, les acteurs des filières animales sont donc appelés à évoluer vers des modes de production durables qui intègrent les aspects économiques, sociaux et environnementaux.

Dans ce contexte, cette dissertation a pour objectifs de caractériser les émissions d'ammoniac et de gaz à effet de serre relatifs à l'élevage de porcs selon différentes modalités d'hébergement et de pointer les facteurs de variation permettant de dégager des voies possibles de réduction. Après une revue de la littérature traitant des paramètres influençant les émissions d'ammoniac d'une part (Philippe et al., 2011b) et de gaz à effet de serre d'autre part, la phase expérimentale s'articule autour de six publications portant sur les effets du type de sol sur les émissions polluantes. Deux articles comparent les émissions gazeuses lors de l'élevage sur caillebotis ou sur litière de paille accumulée pour des porcs charcutiers (Philippe et al., 2007a) et des truies gestantes (Philippe et al., 2009). En vue d'approfondir certaines questions soulevées par ces recherches, des études complémentaires ont été réalisées. L'effet de la taille de la surface paillée a été étudié chez les truies gestantes (Philippe et al., 2010). L'influence du taux de paillage a été abordé chez le porc charcutier (Philippe et al., 2014).

L'évacuation fréquente du fumier par la mise en place d'une litière dite « glissante » est traitée pour le porc charcutier (Philippe et al., 2012). Enfin, un mode de logement combinant sol paillé et sol bétonné a été étudié chez les truies gestantes (Philippe et al., 2013a). Ce travail se termine par une discussion générale intégrant l'ensemble des résultats publiés et s'ouvrant sur des conclusions et perspectives.

2. AMMONIAC ET ELEVAGE DE PORCS

L'ammoniac est un gaz polluant qui contribue à la formation de particules fines dans l'atmosphère ainsi qu'aux phénomènes d'acidification et d'eutrophisation des écosystèmes (Krupa et al., 2003). L'agriculture est responsable de 95% des émissions anthropogéniques de NH_3 et l'élevage représente 64% de la production (Galloway et al., 2004; Steinfeld et al., 2006 ; CEIP, 2010). En Europe, la production porcine contribue à raison de 25% des émissions liées à l'élevage (European Environment Agency, 2010). Les bâtiments en sont la source principale, avec environ 50% des émissions (Webb et Misselbrook, 2004 ; Gac et al., 2007). A l'intérieur des porcheries, les propriétés irritantes du NH_3 ont des effets délétères sur la production, la santé et le bien-être des animaux et de l'éleveur (Donham, 2000; Banhazi et al., 2008). Les pertes azotées liées aux émissions de NH_3 représentent également une réduction importante de la valeur fertilisante des effluents d'élevage.

D'ici à 2050, on prévoit un doublement des émissions de NH_3, en raison de la croissance démographique, des changements dans les préférences alimentaires et de l'intensification de l'agriculture (Krupa et al., 2003; Clarisse et al., 2009). Alors que différentes législations imposent une réduction des niveaux d'émissions, il est primordial d'étudier les facteurs influençant la production de NH_3 afin d'identifier des moyens de réduction efficaces.

Les principaux paramètres d'élevage qui ont un impact sur les émissions de NH_3 à partir des porcheries sont le type de sol et les facteurs alimentaires.

Les types de sol généralement utilisés en production porcine sont le système sur caillebotis, avec récolte des déjections sous forme de lisier, ou le système sur litière, avec récolte des déjections sous forme de fumier. Peu d'études ont comparé de manière standardisée ces deux modes de logement quant aux émissions de NH_3. De plus, au sein de chaque système, de nombreuses adaptations ont été développées, avec des répercussions variables sur les niveaux de NH_3. Lors d'utilisation de caillebotis, le type de matériau utilisé (béton, fonte, métal, plastique), le profil des caillebotis et la proportion de surface lattée ont un impact sur les émissions (Aarnink et al., 1996 ;

Timmerman et al., 2007 ; Hamelin et al., 2010). Lors d'utilisation de litière, la nature du substrat (paille, sciure, copeaux, tourbe), la quantité et la fréquence des apports influencent également la production de NH_3 (Jeppsson, 1998 ; Amon et al., 2007 ; Guingand, 2013). De plus, des résultats contradictoires apparaissent parfois dans la littérature quant aux impacts de ces paramètres sur les émissions de NH_3. Des études supplémentaires sont donc nécessaires afin de préciser les effets réels et les interactions possibles entre ces différents facteurs de variation.

La composition de l'aliment a également des répercussions sur la quantité de NH_3 produite. Une meilleure adéquation des apports alimentaires en fonction des besoins physiologiques et de production des animaux permet de réduire les émissions de NH_3. (Dourmad et al., 1999; Aarnink et Verstegen, 2007). Ainsi, la diminution du taux de protéines de la ration combinée à une supplémentation en acides aminés de synthèse permet d'abaisser les niveaux de NH_3 produit sans entraver les performances de croissance (Philippe et al., 2006 ; Hansen et al., 2007). L'introduction dans l'aliment de matières premières riches en fibres permet également de diminuer la production de NH_3 (Garry et al., 2007 ; Philippe et al., 2008). Cette dernière technique présente cependant le désavantage d'augmenter les émissions de CH_4, puissant gaz à effet de serre, et de détériorer les performances de croissance en cas d'incorporation trop importante (Philippe et al., 2013b). L'ajout d'additifs alimentaires tels l'acide benzoïque, les zéolites et certains probiotiques (*Bacillus subtilis* et *Bacillus licheniformis*) semble également efficace dans la réduction des émissions de NH_3 (Leung et al., 2007 ; Hansen et al., 2007 ; Wang et al., 2009). Souvent testés en laboratoire à partir d'échantillons d'urine et de matières fécales, ces additifs devraient faire l'objet d'expériences en conditions réelles afin de valider leur efficacité sur le terrain .

De nombreux autres facteurs influencent également le niveau des émissions de NH_3 à partir des porcheries. On peut citer les conditions d'ambiance dans le bâtiment (température, ventilation, humidité relative), le mode d'évacuation des effluents et les paramètres liés aux animaux (stade physiologique, sexe, lignée génétique, niveau de performance). Ces différents éléments sont développés dans la synthèse qui suit, publiées dans la revue *Agriculture, Ecosystems and Environment*.

Ammonia emissions from pig houses: influencing factors and mitigation techniques

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Keywords

Ammonia – Pig – Housing conditions – Diet – Manure

Abstract

Pig houses are important sources of ammonia (NH_3) emissions. For decades, investigations were carried out in determine the influencing factors and to point out opportunities of mitigation. In Europe, current NH_3 emissions associated to pig production are about 24% lower than in 1990. However, further reduction seems necessary to avoid noxious effects on ecosystems. The main factors influencing NH_3 production are the floor type, the manure removal system, the climatic conditions inside the building, the diet composition and the feed efficiency of animals.

In pig production, the main floor types are the slatted floor and the bedded floor systems. In both systems, numerous variants and adaptations can be found with consequently a range of emission levels for each housing condition. Therefore, decision in favour of a floor type as regards NH_3 emissions is difficult, especially as effective reducing strategies are available for both systems. For litter-based systems, the nature and the amount of substrate greatly influence the NH_3 production with usually lower emission in case of generous bedding. For slatted floor systems, most of the studies resulted in lower emissions with partly slatted floor on condition that the solid part of the floor remains clean. Indeed, hot conditions, high animal density or inadequate pen design can increase the soiling of the solid floor and lead to increased NH_3 emissions. In any case, emissions are lower if concrete slats are replaced by smooth materials like iron cast, metal or plastic slats.

Several slurry pit designs and manure removal strategies were developed to mitigate emissions. The reduction of the slurry pit surface thanks to sloped pit walls are related

to proportional reductions of NH_3 emissions. Frequent manure removal, flushing and separating urine from faeces by V-shaped scraper or conveyor belts reduce the NH_3 releases from the buildings by about 50%. However, the emissions during the storage period outside the building have to be taken into account for a whole assessment of the technique.

Climate conditions inside the building also influence the emissions which are positively correlated with ambient temperature and ventilation rate. Consequently, ammonia emissions present seasonal and nychtemeral patterns. But, reducing the NH_3 production by modulation of the climate conditions is rather unpractical because the ambient parameters must primarily respect the bioclimatic requirements for animal comfort.

A closer match between dietary intakes and requirement of the pigs according to the physiological and growth stage results in lower NH_3 emissions. In this way, diets with reduced crude protein content are highly effective in reducing the emissions with almost a 10% reduction for every 10 g kg^{-1} reduction in dietary crude protein. Other dietary strategies are also effective in lowering emissions. Dietary fibre inclusion reduces NH_3 emissions by about 40% by shifting the nitrogen from urine to faeces due to promotion of bacterial growth in the large intestine. Lowering the dietary electrolyte balance or supplementation with acidifying salts like benzoic acid or $CaSO_4$ are related to significant reductions. Other feed additives like Yucca extract, zeolites, probiotics, humic substance or lactose were also validated by several experiments. Moreover, better feed efficiency obtained by genetic selection or modification of the hormonal status of the pigs is also related to reduced emissions.

In conclusion, effective reduction of ammonia emissions from pig buildings can be reached operating both on housing conditions and feeding strategies. The former are very efficient but the assessment has to include the specificity of each system and involve the complete process. In some cases, investment and cost operating can hamper their development. Feeding strategies offer the advantage of being easy to implement and rapid to adapt function of particular circumstances.

1. Introduction

Ammonia (NH_3) is an important pollutant gas that accelerates fine particulate formation in the atmosphere and plays a crucial role in the acidification and the eutrophication of ecosystems (Krupa et al., 2003). The largest emitters are China, the European Union and the United States with 15.2, 3.8 and 3.7 Tg NH_3 per year, respectively (European

Environment Agency, 2010; US Environmental Protection Agency, 2005; Zhang et al., 2010). Ammonia largely originates from agriculture which represents about 95% of anthropogenic emissions (Galloway et al., 2004; CEIP, 2010), as presented on Figure 1. Livestock wastes account for 39% of global emissions.

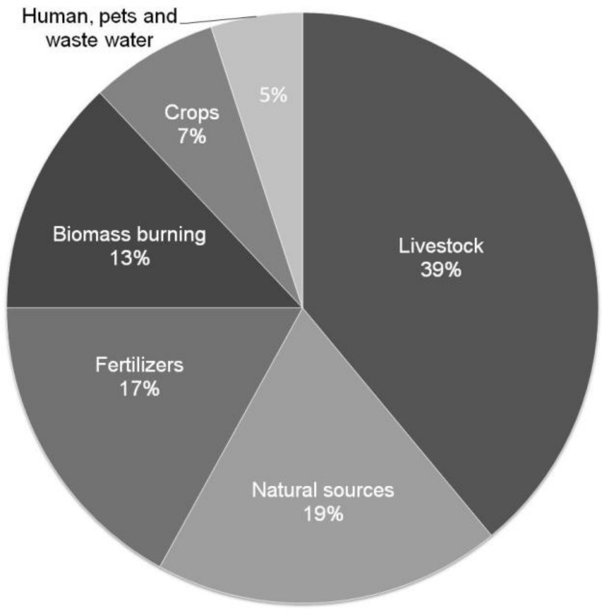

Figure 1 – Repartition of sources of global ammonia emissions (Galloway et al., 2004)

Pig production is globally responsible for about 15% of NH_3-emissions associated to livestock, with a large variation by country (Olivier et al., 1998). In Europe, pig production represents nearby 25% of the livestock emissions (European Environment Agency, 2010). Releases from buildings are the main source, accounting for about 50% of pig NH_3 (Table 1). Compared to other livestock species, housing emission factors of pigs are intermediate. Misselbrook et al. (2000) present daily housing emission factors of 34.3, 79.2 and 146.4 g NH_3 per livestock unit (LU, equivalent to 500 kg live weight) for dairy/beef cattle, fattening pigs and laying hens, respectively. In livestock buildings, NH_3 is a notorious irritating gas resulting in adverse effects on production, health and welfare (Banhazi et al., 2008). Clinical signs include coughing, sneezing, salivation, excessive lachrymal secretions, loss of appetite and lethargic behaviour (Donham, 2000; Kim et al., 2008b). Nitrogen (N) losses via NH_3 emissions also represent a significant reduction of the fertilizer value of animal manure.

Table 1 – Contribution of management stage in swine ammonia emissions in some countries.

Country	Buildings	Storage	Spreading	Outdoor	Reference
France	46%	9%	45%	0%	Gac et al., 2007
United Kingdom	55%	5%	37%	3%	Webb and Misselbrook, 2004
Denmark	51%	20%	29%	0%	Hutchings et al., 2001

For a few decades, international regulations aimed to reduce NH_3 emissions. Thus, current NH_3 emissions are about 20% lower than in 1990, for the 51 countries that ratified the Convention on long-range transboundary air pollution (UNECE, 2007). For Europe, NH_3 emission associated to pig production are reduced by 24% from 1990 to 2008 (Figure 2a) while pig production increased by 19% (Figure 2b) and pig consumption remained quite stable (Figure 2c)

By 2050, the global emissions of NH_3 are expected to double, principally owing to the demographic growth, the changes in food preferences and the agricultural intensification (Krupa et al., 2003; Clarisse et al., 2009). For example, the worldwide pig consumption is expected to increase by 75% in 2020 (Fiala, 2008). Furthermore, large uncertainties remain in the magnitude of NH_3 emissions (Reidy et al., 2008). A recent study using satellite monitoring suggests that NH_3 emissions have been significantly underestimated, especially in the Northern hemisphere (Clarisse et al., 2009). Moreover, evidence of adverse effects on sensitive ecosystems has been found below the current critical level for NH_3 in Europe (Cape et al., 2009). Therefore, the precise knowledge of influencing factors is greatly needed to determine accurate emission factors.
Thus, the aims of this article are to describe the NH_3 production process occurring in livestock manure and to specify the factors that impact on emissions from pig buildings, with focus on the effects of the housing and climate conditions, the animals, the diets and the manure removal strategies.

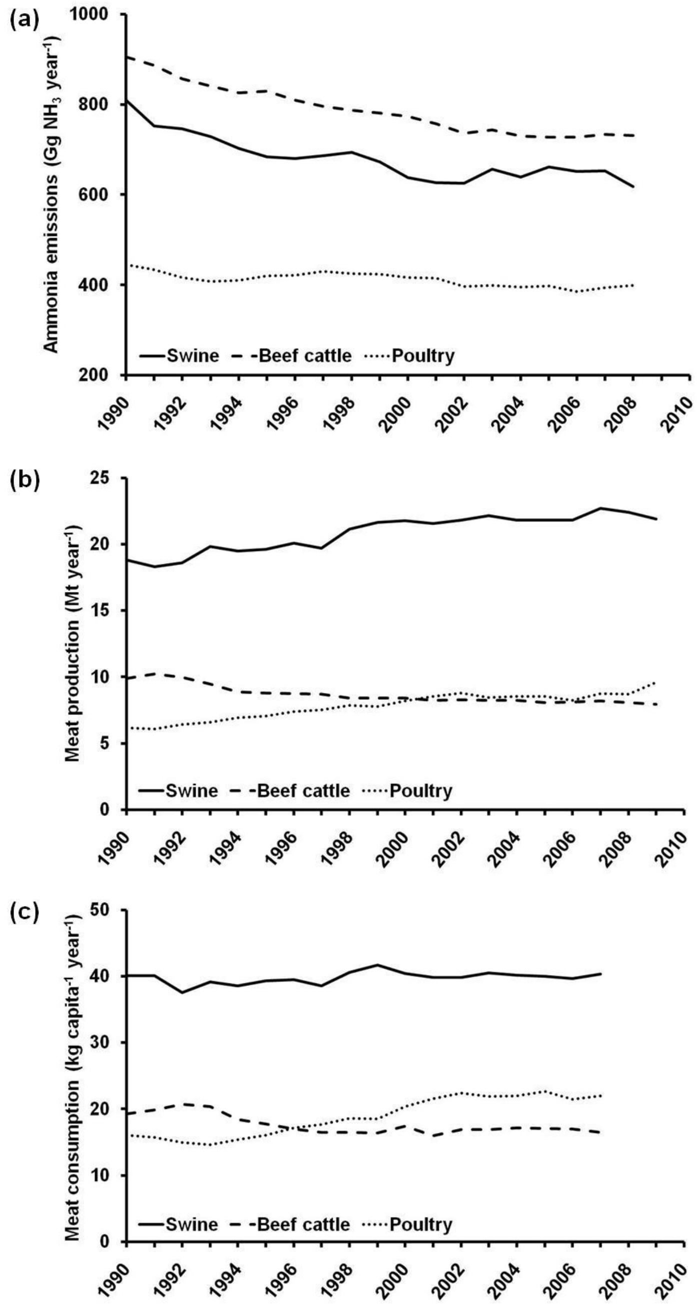

Figure 2 – Trends in (a) ammonia emissions, (b) meat production and (c) meat consumption related to livestock animal categories in European Union (27 countries) from 1990 (European Environment Agency, 2010; FAOSTAT, 2010).

2. Nitrogen transformations and ammonia production in manure

Nitrogen transformations occurring in livestock manure (Figure 3) include mineralization of organic N into NH_3, N assimilation into organic matter, nitrification into nitrite (NO_2^-) and then into nitrate (NO_3^-), and finally denitrification into dinitrogen (N_2) with nitrous oxide (N_2O) as a potential by-product.

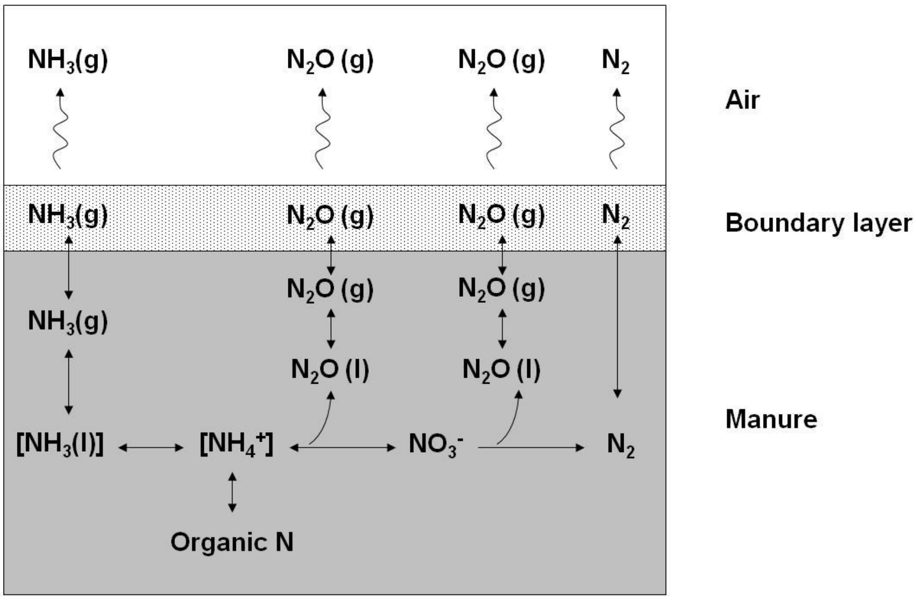

Figure 3 – Nitrogen (N) transformation in livestock manure and releases to the atmosphere (NH_3, ammonia; NH_4^+, ammonium; NO_3^-, nitrate; N_2O, nitrous oxide; N_2, dinitrogen; g, gaseous form; l, liquid form) (adapted from Sommer et al., 2006).

2.1. Ammonia production and emission

2.1.1. Ureolysis

Ammonia originates from mineralization of organic N performed by heterotrophic bacteria. This catabolitic pathway supplies energy needed for bacterial growth. In livestock production, the main source of NH_3 is the rapid hydrolysis of urea of urine by the faecal enzyme urease leading to ammonium (NH_4^+) formation in an aqueous medium (Cortus et al., 2008). Another source of NH_3 is the degradation of undigested proteins, but this way is slow and of secondary importance (Zeeman, 1991). The biochemical processes of ureolysis can be simplified as follows:

$$CO(NH_2)_2 + 3\ H_2O \xrightarrow{\text{Urease}} 2\ NH_4^+ + HCO_3^- + OH^- \quad (1)$$

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. Indeed, the rate of urea hydrolysis depends on the urea concentration up to a threshold from which ureolysis is limited and that corresponds to maximal urease activity (Braam et al., 1997). The NH_4^+ production is also dependent 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).

2.1.2. Dissociation

In liquid phase (l), total ammoniacal N (TAN) is in a state of equilibrium between ionised NH_4^+ and unionised NH_3:

$$NH_4^+ (l) \longleftrightarrow NH_3 (l) + H^+ \quad (2)$$

This equilibrium is influenced by temperature and pH (Figure 4). Higher temperature favour NH_3 concentrations, because of the positive influence of temperature on the dissociation constant K_a, which is defined as:

$$K_a = [NH_3] [H_3O+] / [NH_4^+] \quad (3)$$

The influence of pH is very pronounced. At pH values below 7, nearly all TAN is present in ionised form. At pH above 7, the unionised fraction increases greatly and at pH values of 11 or higher TAN is mainly in the form of NH_3.

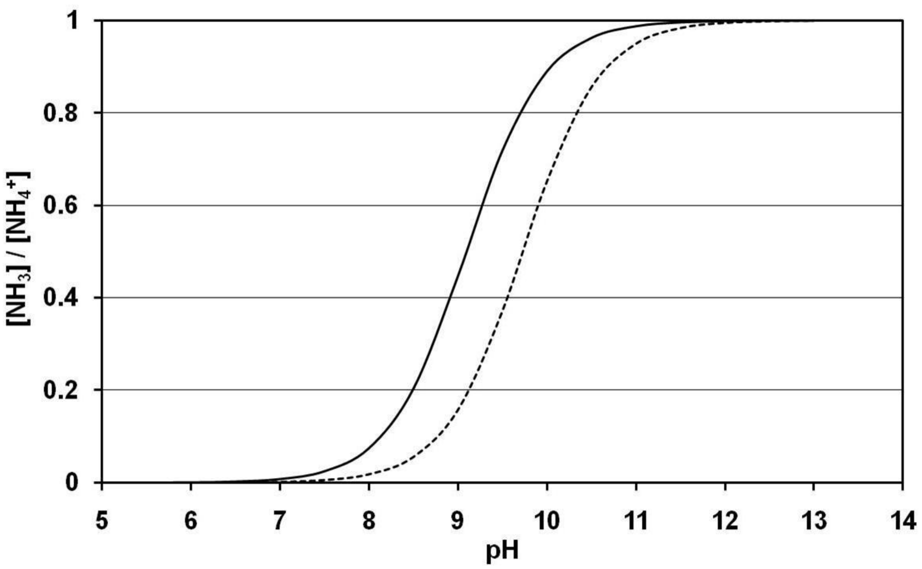

Figure 4 – Influence of pH and temperature on dissociation equilibrium between un-ionised ammonia (NH_3) and ionised ammonium (NH_4^+) in liquid phase (solid line: 30°C; dotted line: 10°C; adapted from Florida Department of Environmental Protection, 2001)

2.1.3. Volatilization

Volatilization of NH_3 to the gaseous phase (g)is controlled by Henry's law. The partial pressure of NH_3 (g), is proportional to the NH_3 (l) concentration (Groot Koerkamp et al., 1998):

$$NH_3\ (l) \longleftrightarrow NH_3\ (g)\quad (4)$$

This equilibrium is strictly temperature dependent with higher temperatures resulting in a higher amount of NH_3 (g). Ammonia volatilization rate (equation 5) is the product of the NH_3 mass transfer coefficient and the difference in partial pressure between the two media (the boundary layer and the air):

$$NH_3\ (g,\ boundary) \longleftrightarrow NH_3\ (g,\ air)\quad (5)$$

The mass transfer coefficient for NH_3 depends on temperature, air velocity at the boundary layer and emitting surface area (Monteny and Erisman, 1998).

Table 2 summarizes the chemical and physical influencing factors for each step of NH_3 production and emission.

Table 2 - Chemical and physical influencing factors of ammonia production and emission (+: the factor increases emissions; -: the factor has no deep influence on emissions)

	T°	pH	[urea]	Air velocity	Air surface Area
Ureolysis	+	-	+	-	-
Dissociation	+	+	-	-	-
Volatilization	+	-	-	+	+

2.2. Assimilation

The N assimilation or immobilization is the incorporation of NH_3 into organic compounds by bacterial process. It may occur under both aerobic and anaerobic conditions but is higher under aerobic conditions (Kermarrec, 1999). It depends on the C/N ratio of degradable organic compounds: when the C/N ratio is high, inorganic N is immobilized into microbial biomass. Ratios of at least 30 are necessary for this process (Groot Koerkamp, 1994). Therefore, in slurry stored in an anaerobic environment and in which the C/N ratio ranges from 4 to 10, practically no assimilation takes place (Chadwick et al., 2000). By contrast, additions of straw and litter systems increase the amount of degradable carbon, favour aerobic conditions and thus induce assimilation (Sommer et al., 2006).

2.3. Nitrification and denitrification

Nitrification is the oxidation of TAN into NO_2^- (nitritation) and then into NO_3^- (nitratation) by Nitrobacteracae. Typical NH_3-oxydizers are *Nitrosomonas*, while typical NO_2^--oxydizers are *Nitrobacter*. Nitrobacteracae are obligate autotrophs and aerobes (Kermarrec, 1999). Denitrification is the reduction of NO_3^- or NO_2^- into inert N_2. This process allows some facultative aerobic bacteria to cover their energy requirements in case of a lack of oxygen (O_2)(Kermarrec, 1999). In slurry, nitrifying activity develops only slowly at the air-manure interface because diffusion of molecular O_2 into the slurry is low and TAN and NO_2^- are not very effective energy sources (Sommer et al., 2006). In litter, heterogenous conditions are met with a combination of aerobic and anaerobic areas. Therefore, significant nitrifying activity can be developed in aerobic regions and nitrate and nitrite produced can diffuse to anaerobic regions where they are denitrifyied into N_2 (Veeken et al., 2002). Moreover, significant emissions of N_2O can be produced as a by-product during these processes in suboptimal conditions (Philippe et al., 2009).

3. Factors influencing ammonia emissions from buildings

3.1. Housing and climate conditions

3.1.1. Floor type

In pig production, the main housing conditions are based on slatted floor or bedded floor.

3.1.1.1. Slatted floor systems

Pigs are usually kept on concrete slatted floors with a slurry pit underneath. Good drainage of manure through the 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 % (Aarnink et al., 1997; Timmerman et al., 2003; Pedersen and Ravn, 2008). However, the installation of these materials is not always suitable for welfare, health, technical or practical reasons. Plastic slats are not appropriate to heavy pigs. Metal slats can cause skin, limb and foot lesions with consequently adverse effects on performance and animal welfare (Lewis et al., 2005). Moreover, the cost of these materials is significantly higher than concrete.

The profile of the slats has to be designed in order to avoid manure lodging between slats. Thus, trapezoidal cross section favours manure drainage (Figure 5), with better results from protruding (Svennerstedt, 1999) or sharp edges (Ye et al., 2007; Hamelin et al., 2010). Contrarily, curved cross-section or epoxy coating seems to be inefficient in reducing NH_3 emissions (Hamelin et al., 2010).

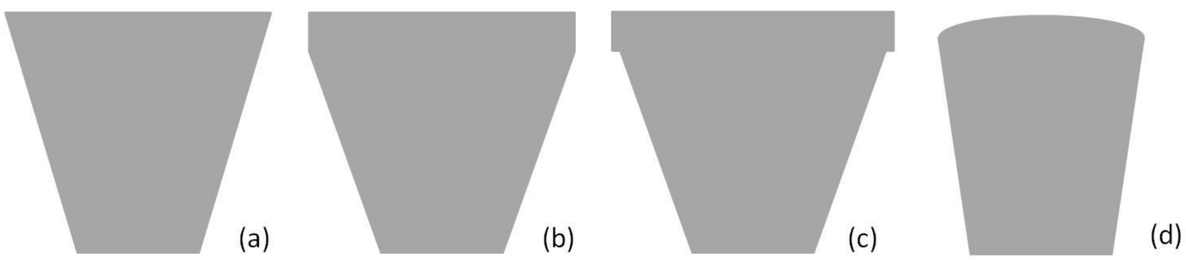

Figure 5 - Profiles of slatted floors: trapezoidal section with sharp edges (a), without beveled edges (b),with protruding edges (c) or with curved surface (adapted from Aarnink et al., 1997; Svennerstadt et al., 1999,Ye et al., 2007 and Hamelin et al., 2010)

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 size of the slats must also integrate welfare concerns. Thus, European legislation (Directive 2008/120/EC) fixes the maximum opening widths and the minimum slat width for concrete slatted floors. For example, references for fattening pigs are 18 mm and 80 mm, respectively.

Compared to a fully slatted floor system, partly slatted floor system produces lower levels of NH_3, as confirmed by numerous studies (Groot Koerkamp et al., 1998; Sun et al., 2008; Ye et al., 2009). 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). These results are explained by a reduction of slurry pit area combined with rather clean solid floors. On the other hand, some studies show higher emissions with partially slatted floors (Guingand and Granier, 2001; Guingand, 2003a; Philippe et al., 2010). According to Guingand and Granier (2001), NH_3 emissions are increased by about 80% with partially slatted floors (50% of pen floor area), but only during summer time.

Actually, NH_3 emissions are clearly correlated with excretory/lying behaviour, ambient temperature and animal density (Guingand et al., 2010). Usually, pigs define separate areas for feeding, lying and excreting purposes, if the environment permits. Thus, pigs prefer to lie in warmer areas with comfortable solid floor and excrete in the coolest part of the pen on slatted floor (Hacker et al., 1994). But under hot conditions, pigs tend to foul the solid area in an attempt to create a wallow to cool themselves by evaporation (Guingand, 2003a; Huynh et al., 2005 Aarnink et al., 2006). Similarly, in the last finishing period, solid lying areas are often fouled with excreta as a consequence of insufficient area (Aarnink et al., 1996 and 2006). The installation of a sprinkler to cool the animals or maintaining an adequate animal density could prevent increasing of NH_3 emissions from partly slatted floor, under particular conditions. 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). Therefore, in order to limit the NH_3 emissions, the slatted floor would be preferably located at the back of the pen with open pen partition in this area (Aarnink et al., 1996).

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). In this way, excretion behaviour increased on the slatted floor and the fouling area decreased on the solid floor causing significant reduction of NH_3 emissions compared to a concrete partly slatted floor (-36%).

Other pen designs were developed to reduce the dirtiness of the pen and then to reduce the NH_3 emissions. However, some of these innovative systems were inefficient. For instance, den Brok and Hendriks (1995) designed a triangular pen for 12 fattening pigs (0.7 m^2 per pig) with feeders in two corners and a slatted floor for excretory behaviour at the opposite side. However, they failed to reduce the emissions because of the soiling of the solid floor. Recently, Lemay et al. (2010) designed a pen with partially slatted floor (40%) covered by an enclosed dunging area that is separately ventilated from the main airspace. They argued that the low ventilation rate from the enclosed dunging area could significantly reduce the NH_3 emissions from the entire building. However, despite numerous pen design adaptations, dunging events occurred outside the enclosed dunging area and negated the potential benefits of this housing system.

3.1.1.2. Bedded systems

For the past few decades, bedded systems have met with renewed interest, as they are associated with improved welfare and a better brand image of livestock production

(Tuyttens, 2005). However, these systems are associated with increased cost (+ 5-10% compared to slatted floor systems) principally due to the straw use and the labour for litter management (Philippe et al., 2006b).

Numerous kinds of bedded systems can be found regarding the litter management. Indeed, the substrate, the amount and the frequency of supply, the litter treatment and the removal strategy (see 3.4 section) may differ from a system to another with significant impact on NH_3 emissions.

Comparisons between bedded systems and traditional slatted floor systems show conflicting results whatever the physiological stage of animals or the substrate, as presented on Table 3. Greater emissions from bedded systems are partly explained by the larger space allowance needed to ensure the proper performance of the bacterial processes in the litter. Ammonia production may also be promoted by the combination of high NH_4^+ content, high pH and high temperature due to aerobic microbial activity in the litter (Dewes, 1996; Philippe et al., 2007a). On the other hand, N assimilation and nitrification/denitrification processes occurring in manure can reduce NH_3 emissions (Kermarrec, 1999; Veeken et al., 2002).

Table 3 – Comparison of ammonia (NH_3) emission factors associated with the slatted floor and litter systems

Pig types	NH_3 (g pig^{-1} day^{-1})		NH_3 (g m^{-2} day^{-1})		Litter characteristics		References
	Slats	Litter	Slats	Litter	Substrate	Amount (kg pig^{-1} day^{-1})	
Gestating sows	12.8	9.1	5.1	3.6	Straw	0.92	Philippe et al. (2010)
Weaned pigs	0.38	0.74	1.21	1.37	Straw	0.09	Cabaraux et al. (2009)
	0.44	0.67	1.41	1.24	Sawdust	0.31	Cabaraux et al. (2009)
Fattening pigs	6.5	11.2	10.8	7.0	Straw	0.71	Balsdon et al., (2000)
	6.7	3.5	10.0	2.9	Sawdust	-	Kermarrec et al., (2002)
	6.9	6.0	9.2	4.3	Straw	2.00	Kavolelis (2006)
	6.2	13.1	8.3	10.9	Straw	0.39	Philippe et al., (2007a)
	7.3	2.0	5.4	1.5	Straw or sawdust	-	Kim et al. (2008a)

Several bedding materials were tested in regards to emissions. The most frequent substrates are straw and sawdust, but wood shaving and peat can also be used (Jeppsson, 1998; Robin et al., 1999; Nicks et al., 2004). Ammonia emissions from sawdust-based deep litter seem to be lower than from straw-based deep litter. Indeed, during the raising of five successive batches of weaned piglets on the same litter, Nicks et al. (2003) obtained reduced emissions with sawdust- compared to straw-based litter (0.46 vs. 1.21 g NH_3 pig^{-1} day^{-1}), while the C/N ratio of the collected manures were 9.7 and 7.0, respectively. However, in this experiment, N_2O emissions were 3.9 times higher with sawdust. Such increase in N_2O emissions associated to a decrease in NH_3 emissions was also observed when comparing gaseous emissions from deep-litter pens with straw or sawdust for fattening pigs (Nicks et al., 2004). The mixture of peat and straw together have many qualities to reduce emissions with low pH, high C/N ratio and availability of degradable carbohydrates as an energy source for N immobilization (Jeppsson, 1998). So, in a uninsulated and naturally ventilated deep litter house for fattening pigs, emissions were reduced by 60% with a mixture of peat (60%) and straw (40%) compared to chopped straw as substrate (Jeppsson, 1998).

Amount of substrate may also impact on NH_3 releases with typically lower emissions related to increasing substrate due to higher C/N ratio (Dewes, 1996; Sommer et al., 2006; Philippe et al., 2010). Barn experiments with fattening pigs show a decrease of emissions by 18% with regular broadcast straw supplies of 8 kg pig^{-1} $week^{-1}$ compared to 4 kg pig^{-1} $week^{-1}$(Gilhespy et al., 2009). In case of targeted straw supply to the most soiled areas, the use of 4 kg pig^{-1} $week^{-1}$ compared to 2 kg pig^{-1} $week^{-1}$ is sufficient to significantly reduced emissions (-39%), whereas straw addition until 8 kg pig^{-1} $week^{-1}$ failed to further reduce emissions.

The physical structure as well as density and moisture content of the litter influence emissions thanks to the effect on gas diffusion, protection from air turbulence and capacity to absorb NH_3 (Dewes, 1996). With sawdust based systems, Groenestein and van Faassen (1996) observed a reduction of emissions (-50%) with a 70 cm-thick bed associated with a weekly superficial incorporation of the manure compared to a 50 cm-thick bed associated with a weekly deep incorporation of the manure. Kaiser and Van den Weghe (1997) tested a turn-over treatment with rotating mixers in deep litter systems and obtained reduced NH_3 emissions (4.5 vs. 8.3 g NH_3 pig^{-1} day^{-1}) but higher

N_2O emissions (6.5 vs. 0.0 g N_2O pig^{-1} day^{-1}) with sawdust compared to straw as substartes. Indeed, despite turn-over operations, anaerobic conditions were met within the sawdust litter, leading to suboptimal conditions for complete nitrification/denitrification with pollutant emissions of N_2O instead of inert N_2 as a result (Philippe et al., 2009).

In order to stimulate the separation of the excretory and lying behaviours, some of litter-based housing systems are associated with slatted floor and/or solid floor. Thus, 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^{-1}) and a slatted floor area at the back of the pen for dunging (0.25 m^2 pig^{-1}). With straw-based litters, emissions were around 20-25 g NH_3 pig^{-1} day^{-1}. 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^{-1}), and a deep litter as excreting area (0.54 m^2 pig^{-1}) resulted in lower emissions, with on average 8.3 g NH_3 pig^{-1} day^{-1} (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.

3.1.2. Ambient temperature and relative humidity

Ammonia emissions are positively related to ambient temperature (Granier et al., 1996; Cortus et al., 2008). As mentioned before, temperature has direct effects on emissions favouring urease activity, dissociation and volatilization from manure, but also indirect effects via pig behaviour. Indeed, the degree of floor fouling greatly depends on the inside temperature (Aarnink et al., 1996; Huynh et al., 2005). However, few experiments consider only temperature effects because of the interlinked effect of ventilation flow. Under laboratory conditions, Cortus et al. (2008) studied the effect of increasing temperature with constant air flow and found twofold emissions when temperature shifts from 10° to 20°C. Under barn conditions, the effect seems to be lower with daily emissions increasing from 12.8 to 14.6 g NH_3 pig^{-1} when the temperature increased from 17° to 28°C (Granier et al., 1996).

Studies have observed that the relative humidity was negatively correlated with NH_3 emissions (Blunden et al., 2008; Cortus et al., 2008). It seems, though, that this is not the primary cause of variation but a secondary factor, itself influenced by room temperature and ventilation rate.

3.1.3. Ventilation

3.1.3.1. Ventilation rate and ventilation type

The influence of ventilation rate has been investigated in several studies, with consensually higher NH_3 emission related to increasing air flow rate (Aarnink and Wagemans, 1997; Blunden et al, 2008; Blanes-Vidal et al., 2008; Ye et al., 2009). With fattening pigs on fully slatted floors, when ventilation rate was increased from 9.3 to 25.7 m^3 h^{-1} pig^{-1}, emissions increased by 25%, while concentration in the building was three times lower due to a dilution effect (Granier et al., 1996). In an unsinsulated building for fattening pigs kept on litter, Jeppsson (2002) observed three-fold NH_3 emissions while ventilation rate was five-fold. It is explained by the increased air exchange rate above the emitting area.

Gallmann et al. (2003) compared mechanically and naturally ventilated pig facilities with higher emissions from the former (+47%), partly explained by the higher temperature inside the room.

The location of the air outlets and inlets has little influence on the NH_3 emissions. Comparing high or floor air extraction, Aarnink and Wagemans (1997) did not observed any difference between systems. Massabie et al. (1999) noticed similar emission for under and over-floor extraction. An extra pit ventilation system in combination with a ceiling ventilation system did not modified the whole building emission levels compared with only ceiling ventilation system (Saha et al., 2010). However, Hayes et al. (2006) reported enhanced volatilization related to high air velocity near the manure surface due to the location of the fans. In all cases, air quality inside the building is actually affected by the ventilation system, with lower NH_3 concentration associated with floor or pit air extraction (Aarnink and Wagemans, 1997; Massabie et al., 1999; Saha et al., 2010). Indeed, the location of the outlets near the main source of contaminants improves inside air quality.

Despite the great influence of ventilation rate and ambient temperature, using climate conditions to modulate NH_3 production is a rather unpractical mean because the ambient parameters must primarily respect the bioclimatic comfort of the animals.

3.1.3.2. Air scrubbers

Air scrubbers are techniques developed to reduce pollutant and odorous compounds from the exhaust air of livestock facilities. There are two main types of air scrubbers: acid scrubber and biofilter. Schematically (Figure 6), air exhausted from the building is connected by a duct to a reactor filled with a packing material. Media consist of inert or inorganic material (scrubber), or a mixture of compost, wood chips, peat, soil or rockwool (biofiltration) (Martens et al., 2001; Jacobson et al., 2003; Melse et al., 2009; Yasuda et al., 2009). A humidifier or a sprinkler is incorporated in the design to maintain moisture content between 40 and 60% (Sheridan et al., 2002; Kastner et al., 2004). A part of the water is continuously recycled; another fraction is discharged and replaced by fresh water.

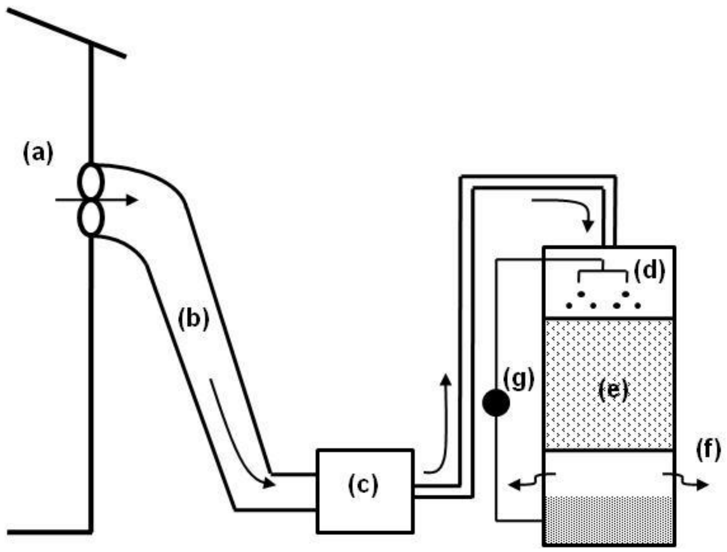

Figure 6 – Schematic view of air scrubber system (adapted from Deshusses et al., 1997): (a) exhaust fan, (b) air duct, (c) humidifier, (d) splinker zone, (e) packing media, (f) air outlet, (g) pump.

In an acid scrubber, the pH of the recycled water is kept below 4 by the addition of acid, usually sulphuric acid. The gaseous NH_3 dissolves in the liquid phase and is captured by the acid forming soluble NH_4^+(Melse et al., 2009).

In a biofilter, media is inoculated with specific aerobic microorganisms in order to transform inorganic compounds or to break down organic compounds (Deshusses, 1997). Thus, NH_3 is oxidized into NO_2^- and NO_3^-. Further reduction into non-polluting N_2 by denitrification is also reported (Ho et al., 2008).

Data from finishing pig houses presented NH_3 reductions ranging from 65 to 95 % with the two types of air scrubber (Sheridan et al., 2002; Melse et al., 2009; Yasuda et al., 2009). Removal efficiencies depend on inlet NH_3 concentration, residence time, moisture content, temperature, O_2 level, pH and media characteristics (Sheridan et al., 2002; Kastner et al., 2004; Chen et al., 2008; Melse et al., 2009).

Unfortunately, this very efficient technique is quite expensive because of high investment and operational costs related to energy cost, chemical and filter use and maintenance (Melse et al., 2009). Melse and Willers (2004) estimated the cost of air cleaning between 7 € and 19 € per kg NH_3 removal for the Netherlands. Therefore, improving the cost-efficiency of air scrubber would be necessary to promote largely the system.

3.1.4. Seasonal and nychtemeral variations

Ammonia emissions are obviously influenced by season with typically higher emission rates during summertime and lower emission during wintertime. Aarnink et al. (1997) found winter emissions around 5.7 g NH_3 pig^{-1} day^{-1} and summer emissions around 7.6 g NH_3 pig^{-1} day^{-1}. For Harper et al. (2004), winter and summer emissions are 3.3 and 7.0 g NH_3 pig^{-1} day^{-1}, respectively. These results are explained by the greater ambient temperature and/or higher ventilation rate in summertime that both promote NH_3 emissions. Ammonia emissions also show diurnal variations with day/night ratio ranging from 1.1 to 2.0 (Aarnink et al., 1996; Guarino et al., 2003; Harper et al., 2004). Indeed, NH_3 emissions are highly correlated with animal activity (Delcourt et al., 2001; de Sousa and Pedersen, 2004; Blanes-Vidal et al., 2008), and especially with feeding and excretory behaviour (Groenestein et al., 2003; de Sousa and Pedersen, 2004; Guarino et al., 2008). Guarino et al. (2008) observed that most pigs excreted 1 or 2 h after feeding, with consequent peaks of emissions. Aarnink et al. (1996) obtained linear relationships between animal activity, urinating frequency and NH_3 emission. The diurnal variation of air movement over the floor due to active pigs and ventilation rate as a consequence of increased heat production contribute also to the diurnal NH_3 emission pattern (de Sousa and Pedersen, 2004). These seasonal and nychtemeral variations of NH_3 emissions have to be taken into account for measurement procedures and determination of annual emission factors.

3.2. Animal

3.2.1. Physiological stage

The emission factors associated to physiological stages are presented in Table 4, as reported in the literature either as theoretical references or experimental data. The rearing system on slatted floors was retained for this discussion.

For reproductive sows, emissions are typically greater during lactation than during gestation. On average, the values are around 12.1 g NH_3 day^{-1} for gestating sows and around 21.7 g NH_3 day^{-1} for lactating sows (Table 4). Under field conditions, Hayes et al. (2006) observed an increase of emissions by 40% during lactation compared to gestation (17.1 vs 12.1 g NH_3 day^{-1}). The N consumption and retention are quite different for these two stages. Contrary to a lactation diet, gestation diets are relatively low in crude protein and restrictedly fed. For French pig production, Dourmad et al. (1999) estimated N intakes of 66 and 153 g N day^{-1} and N losses of 53 and 90 g N day^{-1} during gestation and lactation, respectively. In this latter study, NH_3 emissions from the building are evaluated as about 25% of total N excretion, corresponding to 15.9 and 27.3 g NH_3 day^{-1}, respectively. Taking into account the duration of both stages (125 days for dry and pregnant period, 28 days for lactation period) and on the basis of data from Table 4, an emission factor of 2.12 kg NH_3 per reproductive cycle can be proposed, corresponding to about 14 g NH_3 day^{-1}. This is an intermediate value between the theoretical value of van der Hoeck (1998) and the experimental values of Groot Koerkamp et al. (1998) who presented one value for the entire cycle. Ammonia emissions reported for weaned piglets present a large range of variation, with tenfold emissions between the lowest and the highest values. The lowest value (0.41 g NH_3 pig^{-1} day^{-1}) was measured by Cabaraux et al. (2009) who partly explain their results by the presence of a water layer in the bottom of the slurry pit at the beginning of the experiment and by the use of a plastic floor. Relatively low emission levels were also observed by Groot Koerkamp et al. (1998) with values ranging from 0.53 to 1.10 g NH_3 pig^{-1} day^{-1}. During the rearing of weaned piglets on concrete slatted floors, Guingand

(2003b) observed greater emission with 3.5 g NH_3 pig^{-1} day^{-1}. The estimation of NH_3 losses based on 25% of N excreted (Dourmad et al., 1999) presents the highest emission factor with 4.26 g NH_3 pig^{-1} day^{-1}. The large range in published NH_3 emissions may be attributed to differences in house design (eg. type of slatted floor, ventilation system) and management practices (eg. age and weight at weaning, diet formulation). However, according to this literature review, a consensual emission factor can be rationally estimated to about 2 g NH_3 pig^{-1} day^{-1}, but further investigations have to be carried out to specify accurate emission factors for several kinds of piglet rearing systems. For the fattening period, the compilation of theoretical and experimental values seems to converge to a daily emission factor around 9.0 g NH_3 pig^{-1} (Table 4). Ammonia emissions are significantly related to pig weight as confirmed by a model established by Ni et al. (1999). According to Philippe et al. (2007a), emissions are fivefold from the beginning to the end of the fattening period. The mean daily increase is estimated at 85 mg NH_3 pig^{-1} throughout the fattening period (Aarnink et al., 1995). This is due to the increased feeding and manure production as the pigs grow. Expressed per LU, emissions from fattening pigs are evaluated to about 70 g NH_3 day^{-1} (Table 4). This is slightly higher than corresponding values for weaned piglets and lactating sows which are close to 60 and 54 g NH_3 LU^{-1} day^{-1}, respectively. The lower N retention, as a percentage of N intake, for fattening pigs compared to piglets and lactating sows (Dourmad et al., 1999), may explain this result. For gestating sows, the low emission factors (around 30 g NH_3 LU^{-1} day^{-1}) are mainly due to the restricted diets, as presented above. On a global scale, fattening pigs are the main contributors to the total emissions of pig-related NH_3 (70%) while productive sows and weaners are responsible for 20% and 10% of emissions, respectively (Dourmad et al., 1999).

Table 4 – Housing ammonia emissions according to the physiological stage of the pigs (kept on slatted floor)

Reference	Emissions factor (g NH_3 animal^{-1} day^{-1})				Emissions factor (g NH_3 LU^{-1} day^{-1})			
	Gestating sow	Lactating sow	Weaned piglet	Fattening pig	Gestating sow	Lactating sow	Weaned piglet	Fattening pig
Theoretical values								
Hyde et al., 2003	8.3[b]	15.8[b]	1.01[b]	12.5[b]	20.6	35.8	33.6	96.2
Dourmad et al., 1999	15.9	27.3	4.26	11.4	39.7[b]	62.1[b]	142.1[b]	87.5[b]
van der Peet-Schwering et al., 1999	11.5	22.7	1.64	8.2	28.8[b]	51.7[b]	54.8[b]	63.2[b]
van der Hoek, 1998	20.4		-	7.9	48.5[c]		-	60.9[b]
Experimental values								
Philippe et al., 2007a and 2010; Cabaraux et al., 2009[a]	12.8	-	0.41	6.2	30.2	-	13.5	45.9
Hayes et al., 2006	12.1	17.1	1.40	10.0	43.2	61.1	50.0	64.5
Guingand, 2003b	-	25.6	3.45	9.5	-	58.2	101.5	72.1
Groot Koerkamp et al., 1998	12.6		0.72	7.2	31.5		24.3	57.8
Mean	12.1	21.7	1.84	9.1	32.5	53.8	60.0	68.5

LU is equivalent to 500 kg liveweight

[a]: data of these studies were combined because they were obtained under similar experimental conditions

[b]: estimated according to live weights equal to 200 kg, 220 kg, 15 kg, 65 kg for gestating sow, lactating sow, weaned piglet and fattening pig, respectively

[c]: estimated according to live weight equals to 210 kg

3.2.2. Breed, genetic lines and gender

Up to now, there is little data about the influence of breed, genetic line or gender on NH_3 emissions. However, numerous authors have studied the impact of these factors on protein deposition efficiency, especially during the growing period. Better growth performance with high protein deposition rate is related to reduced N output and reduced NH_3 emissions as consequence.

For example, paternal lines like Hampshire or Duroc pigs presented increased N retention and decreased N excretion compared to maternal lines like Landrace pigs (Tauson et al., 1998). Experiments conducted with slow growth breeds, as Creole or Meishan pigs, showed similar daily N output compared to Large White pigs (Renaudeau et al., 2006; Latorre et al., 2008). However, NH_3 emissions expressed per pig could be 50% higher with the slow growth breeds because of the lower protein deposition rate and the longer growing period.

The effect of sex on growth performance and protein retention is clearly proven. Boars have a higher growth capacity than females due to their high plasma concentrations of androgens resulting in an anabolic state that improves feed efficiency and leads to leaner carcasses (Tauson et al., 1998). Thus, a reduction of NH_3 emissions associated with boars is expected but not yet experimentally measured.

In most countries, castration of male pigs is routinely performed in order to prevent the occurrence of boars taint. Surgically castrated pigs are less feed efficient than entire males (Zamaratskaia et al, 2008; Pauly et al., 2009), with consequently higher N outputs and presumed higher NH_3 emissions (Crocker and Robinson, 2002). Compared to surgically castrated pigs, growth performance of immuno-castrated pigs are comparable (Zamaratskaia et al, 2008; Pauly et al., 2009) or even better (Schmoll et al., 2009). Nevertheless, many uncertainties remain about the precise impacts of immuno-castration on outputs, and especially on NH_3 emissions, whereas immuno-castration could become widespread principally for welfare concerns.

3.3. Diet

3.3.1. Crude protein content

Reduced crude protein (CP) diets containing synthetic amino acids have been shown to reduce N excretion, which leads to reduced NH_3 emissions without any detrimental effect on pig performance. Barn experiments with fattening pigs on slatted floors present NH_3 emission reductions between 7 and 15 % for every 10 g kg^{-1} reduction in dietary CP (Canh et al., 1998b; Otto et al., 2003; Hayes et al., 2004; Hansen et al., 2007). With pigs on deep litter, Philippe et al. (2006a) observed a reduction of NH_3 emissions of 8.2 % for every 10 g kg^{-1} reduction in dietary CP. *In vitro* essays on slurry samples show similar results with a reduction of around 8-9% for every 10 g kg^{-1} reduction in dietary CP (Table 5).

Table 5 – Manure pH and reduction levels (per 10 g kg^{-1} reduction in diet crude protein, CP) of ammonia emissions (NH_3) and nitrogen (N) outputs obtained by a decrease of the diet CP content (EN: excreted N; UN: urinary N; FN: fecal N).

CP contents	NH_3	EN	UN	FN	Manure pH	Reference
12.5% vs. 16.5%	10.1%	8.8%	11.2%	0.9%	8.16 vs. 9.14	Canh et al., 1998b
12.0% vs. 20.0%	9.4%	7.0%	8.1%	4.0%	7.57 vs. 8.92	Portejoie et al., 2004
16.0% vs. 22.0%	6.3%	3.8%	4.2%	3.1%	8.23 vs. 8.80	O'Connell et al., 2006
15.0% vs. 20.0%	9.8%	8.4%	10.6%	2.8%	8.16 vs. 9.14	O'Shea et al., 2009

Balance experiments show that CP reduction induces principally a decrease of urinary fraction of excreted N while faecal fraction is less affected (Table 5). Since faecal N is mainly present in the form of proteins, which are less susceptible to rapid decomposition and urinary N is mainly present in the form of urea, which is easily converted into NH_4^+, there is a significant NH_3 reduction with low CP diets. Moreover, these diets lead to a manure pH decrease related to urine acidification due to supplemented amino acids (Sutton et al., 1996). As explained above, a decrease in manure pH impacts greatly on NH_3 dissociation and emissions. Thus, for efficient reduction of excreted N and emitted NH_3, the intakes of proteins and amino acids have to be acutely adjusted to requirements over time (Dourmad et al., 1999; Aarnink et al., 2007). This can be achieved by supplying different diets for the different physiological or growth stages with a closer match between intake and requirement. This feeding strategy is called "phase-feeding". A two-phase feeding program can reduce N excretion and NH_3 emissions by about 15-20% for sows, weaned pigs as well as fattening pigs (Latimier et al., 1993; CORPEN, 2003 and 2006).

Determination of cost effectiveness of dietary manipulation related to low NH_3 emissions makes it difficult principally due to the large fluctuation of raw materials prices depending on market conditions. Thus, the cost of reduced CP diets is greatly affected by the cost of soybean meal and synthetic amino acids. For the 2004-2008 period, Pineiro et al. (2009) evaluated that the cost difference between reduced CP diet and standard diet fluctuated from +5 € to -6 € per pig produced. For the Netherlands, Aarnink et al. (2010) estimated that reduced CP diets are associated to an extra cost around 2 € per place and per year for 10% NH_3 reduction.

3.3.2. Dietary fibre

Reducing NH_3 emissions from the slurry can also be achieved by the addition of fibrous feedstuffs in the diet. Indeed, in the large intestine, easily fermentable non-starch polysaccharides (NSP) enhance bacterial growth and induce urea secretion from the blood into the lumen (Low, 1985). Then, N from transferred urea and from dietary protein can be incorporated into bacterial proteins which are more stable. In this way, the ratio of the excreted N is altered, resulting in reduced N excretion in urine as urea and shifted N excretion in faeces as bacterial proteins. Moreover, fermentable NSP also reduce NH_3 emissions by slurry pH decrease due to volatile fatty acid (VFA) formation during fermentation in large intestine and slurry (Kreuzer et al., 1998; Clark et al., 2005; O'Shea et al., 2009).

Comparing a fibrous diet based on sugar beet pulp (18.5% neutral-detergent fibre, NDF) with a conventional diet based on cereals (12.1% NDF), O'Shea et al. (2009) observed a reduction of NH_3 emissions by 40%, under laboratory conditions. This reduction is explained by the decrease of urinary N (16.8 vs. 20.3 g $N.day^{-1}$) while faecal, excreted and retained N are less affected. The pH of fresh slurry was reduced by 3.36 units (5.59 vs. 8.95) and the VFA concentration was increased from 90 to 120 mmol L^{-1}.

Ammonia emissions can also be influenced by the cereal type and the source of NSP (O'Connell et al., 2006; Garry et al., 2007; Leek et al., 2007). By substituting wheat for barley in the diet for fattening pigs, NH_3 emissions can be reduced by about 40% under field conditions (Garry et al., 2007). The level of fibre degradability affects the magnitude of the response. Soluble dietary fibre rich in cellulose and hemicelluloses and poor in lignin are easily fermentable and consequently more efficient in NH_3 reduction (Garry et al., 2007).

With high fibre diets, the amount of faeces produced and the viscosity of the digesta are increased (Noblet and Le Goff, 2001; Masse et al., 2003). This could increase the dirtiness of the floor and so contribute to higher NH_3 emissions. So, the effective NH_3 reduction obtained with high fibre diets have to be assessed under practical conditions taking into account these parameters. Moreover, it should be remarked that increasing the level of dietary fibre decrease the diet digestibility and promote methane emissions (Philippe et al., 2008). Thus, decision for dietary fibre inclusion has to be considered with regard to the relative importance given to these issues.

3.3.3. Feed additives

3.3.3.1. Non-starch polysaccharides enzymes

Several experiments were conducted to examine the effect of NSP enzyme supplementation on digestibility, pig performance and NH_3 emissions (Garry et al., 2007; Leek et al., 2007; O'Shea et al., 2010). The aim of the enzyme supplementation was to improve pig performance by removing the anti-nutritional effects of fermentable fibre in cereals but without suppressing the beneficial effects of NSP on ammonia emission. The experimental diets were based on barley, wheat or oat, and enzyme supplements were composed of a mixture of β-glucanase and β-xylanase.

While enzyme supplementation has few impacts on digestibility and growth performance, contrasting results were obtained for NH_3 emissions according to the cereal type (Garry et al., 2007; Leek et al., 2007).With barley-based diets, enzyme supplementation increases NH_3 emissions by 30% under practical conditions (Garry et al., 2007; O'Shea et al., 2010). With wheat-based diet, enzyme supplementation decreases NH_3 emissions by 15-20% under laboratory and practical conditions as well (Garry et al., 2007). With oat-based diet, O'Shea et al. (2010) did not observed any effect of enzyme inclusion on NH_3 emissions. These opposed results could be explained by the dissimilarity in the composition of the NSP fraction of these cereals. By example, for barley, the NSP fraction contains a mixture of β-glucans and arabinoxylans, while for wheat, the NSP are mainly constituted of arabinoxylans.

3.3.3.2. Acidifying salts and dietary electrolyte balance

Dietary anion-cation balance impacts NH_3 emissions because of renal regulation to maintain constant blood pH, with an important effect on the pH of urine and slurry (Canh et al., 1998a).

The dietary electrolytic balance (dEB), calculated as ($Na^+ + K^+ - Cl^-$) and expressed in mEq, may be used to evaluate the diet acidogenicity. Under laboratory conditions, Canh et al. (1998a) observed a reduction of the pH of urine and slurry by 0.46 and 0.17 units respectively when dEB decreased from 320 to 100 mEq per kg dry matter. Consequently, the NH_3 emissions are reduced by 11%. Under practical conditions, inclusion of $CaCl_2$ in the diet of weaned piglets decreases emissions by 20%, thanks principally to a reduction of dEB from 343 to -7 mEq kg^{-1} (Colina et al., 2001).

Dietary inclusion of acidifying salts has been tested under laboratory conditions. Adding $CaSO_4$ (1.7%), benzoic acid (1%) or adipic acid (1%) to the diet decreases urinary pH and thus, reduces *in vitro* NH_3 emissions by 5%, 20% and 25% respectively (van Kempen, 2001; Velthof et al., 2005; Guiziou et al., 2006). Canh et al. (1998a) observed a decrease in pH of urine and slurry when $CaCO_3$ was replaced by $CaSO_4$ or Ca-benzoate, resulting in a reduction of NH_3 emissions by 30% and 54%, respectively. According to Daumer et al. (2007), the addition of 1% of benzoic acid decreases emissions by nearly 40%. The effectiveness of the anions benzoate may be explained by the higher buffering capacity of urine related to its rapid metabolisation into hippuric acid, which is excreted in urine. Under practical conditions, the effect of benzoic acid (1-3%) was validated for growing-finishing pigs with NH_3 emission reductions ranging from 16% to 57% (Hansen et al., 2007; Aarnink et al., 2008). However, cost-effectiveness of benzoic acid inclusion is quite expensive. For 10% NH_3 reduction, Aarnink et al. (2010) estimated the costs per place and per year to 6.2 € for benzoic inclusion and to about 2 € for exchange $CaCO_3$ by $CaCl_2$ or $CaSO_4$.

3.3.3.3. Yucca extract

Dietary additives based on the extract from *Yucca schidigera* were tested in order to prevent NH_3 emissions. Studies show reductions ranging from 20% to 30% with dietary inclusion of about 0.01% of Yucca extract (Amon et al., 1995; Colina et al., 2001; Panetta et al., 2006). The effect of Yucca extracts could be associated with glyco-components of its sap, especially saponins. Some have suggested that these components inhibit urease activity and chemically convert or bind NH_3 (Duffy and Brooks, 1998). Benefits could be also attributed to improvements of performance and health status (Colina et al., 2001). Direct application to manure also seems to be effective to reduce emissions (Panetta et al., 2006).

3.3.3.4. Zeolites

Zeolites are microporous aluminosilicate minerals characterized by large internal surface area and high cation exchange capacity. There are more than 50 different types of natural zeolites, each with a selectivity towards various cations (NH_4^+, Na^+, K^+, Ca^{2+}). The clinoptilolite has a specific affinity for the NH_4^+ cation (Milic et al., 2006; Leung et al., 2007). Dietary incorporation of 2 to 4% of zeolites resulted in improved performance as well for growing/finishing stages (Kim et al., 2005; Leung et al., 2007), gestating/lactating stages (Papaioannou et al., 2002), because of its beneficial effect on N retention and protein digestibility (Leung et al., 2007). Therefore, the manure N content is reduced and NH_3 emissions are lowered, as a consequence (Kim et al., 2005; Milic et al., 2006; Tiwari et al., 2009). For example, a decrease of NH_3 emissions by 33% is observed when piglets are fed with 2% clinoptilolite supplemented diet (Milic et al., 2006).

3.3.3.5. Probiotics

The use of probiotic agents in livestock resulted from a demand for alternative strategies to improve animal production and health without the need for antibiotics (Wang et al., 2009). Laboratory experiments concluded in a reduction of NH_3 emission in the case of supplementation of probiotics (Yoo et al., 2007; Wang et al., 2009). According to Wang et al. (2009), probiotic supplements containing *Bacillus subtilis* and *Bacillus licheniformis* spores reduce emissions by about 50% with inclusion rates ranging from 0.05% to 0.2%. Potential explanations are enhanced digestibility, alteration of microbiota favoring lactic acid bacteria and consequently reduced pH of slurry (Cho et al. 2005; Wang et al., 2009). In addition, *Bacillus subtilis* generates subtilin, which may reduce urease-generating microbiota in the gastrointestinal lumen thereby attenuating NH_3releases (Wang et al., 2009). However, some studies failed to show beneficial effects on NH_3 emissions (Han et al., 2005; Cho et al, 2005). Therefore, further investigations are needed to confirm these results and this hypothesis.

3.3.3.6. Other additives

An experiment of Ji et al. (2006) shows a reduction in NH_3 emissions of around 15-20% with dietary inclusion of 0.5% of humic substances. Humic substances are defined as yellow to black colored and high-molecular-weight substances formed by secondary synthesis reactions in soils. It includes humic acid, fulvic acid, and humin as major constituents as well as several minerals such as iron, manganese, copper and zinc. These are known to inhibit the urease activity, especially in an acidic environment (Vaughan and Ord, 1991).

According to Pierce et al. (2006), dietary inclusion of lactose is also effective in reducing NH_3 emissions. The addition of 30 g kg^{-1} of lactose in the diet of finishing pigs decreases emissions by 25% during the initial 4 days of laboratory incubation of collected dejections. The lower lactase activity of older animals results in a reduction of the ability to digest high levels of lactose. Thus, important quantities of undigested lactose may reach the hind-gut, yielding a substrate for bacteria (Kim et al., 1978). Consequently, bacterial activity is promoted, with specifically an increase in the concentration of lactobacilli. As results, the VFA concentration in the large intestine is increased and the urine to faecal N ratio and the slurry pH are reduced with environmentally interesting impacts on NH_3 emissions.

3.3.4. Feed manufacturing, feeding equipment and feeding schedule

Feed manufacturing technologies, such as fine grinding and pelleting, may impact pig emissions by improving the diet digestibility, reducing feed spillage and therefore lowering the N excreted (Ferket et al., 2002). The feedstuff fragmentation increases the surface area of the feed ingredient particles and allows a greater interaction with digestive enzymes. Thus, decreasing the particle size of growing pigs diet from 1000 to 500 µm significantly increases the N digestibility, shifting from 85% to 89% (Lahaye et al., 2004).

Pelleting feed is also effective to improve feed use with increased feed conversion efficiency and average daily gain (Le Gall et al., 2009). The heat treatment associated with the pelleting process improves feed digestibility by deactivating antinutritional factors and increasing starch gelatinization (Ferket et al., 2002). Moreover, the compression process increases the bulk density and reduces the dustiness of the feed, resulting in decreased losses during handling or prehension by animals (Ferket et al., 2002). Studies comparing different pelleting processes show improved N digestibility with greater compression rate (Lahaye et al., 2008) and high flow extrusion (Lahaye et al., 2004).

The design and the position of the feeder and the drinker also influence the NH_3 emissions by minimizing feed spillage (Ferket et al., 2002).

More investigations would be necessary to confirm or deny these presumed effects of feed manufacturing processes and feed equipment on reduction of NH_3 emissions.

The feeding schedule may also impact on NH_3 emission. Groenestein et al. (2003) studied this effect with gestating sows. They observed that, changing the feeding time does not affect the total amount of NH_3 emitted if the animals are fed simultaneously. But when the animals are fed sequentially by the use of an electronic sow feeder, the emission falls by 10% if the feeding starts in the afternoon instead of in the morning because of a modification in the animal activity pattern.

3.4. Manure removal system

With the traditional slatted floor system, the waste is stored in a slurry pit under the slats for long periods and is removed after several months into a storage compartment outside the building. This so-called “deep-pit” system is a concentrated source of emissions as 70-80% of the entire housing emissions originate from the pit (Monteny, 1996). Therefore, several manure management strategies were developed to mitigate emissions. Slurry pit design, frequent manure removal, flushing and separation of urine from faeces are suitable means to diminish NH_3 releases from the building.

Slurry pits were designed to reduce the emitting surface, principally thanks to sloped pit walls. 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 et al., 1998) and with gestating sows (Timmerman et al., 2003).

A fortnightly removal strategy reduces NH_3 emissions by 20% compared to a system where the slurry was stored for the duration of the finishing period (Guingand, 2000). With weekly discharge, emissions decreased by 35% compared to the traditional deep-pit system (Guarino et al., 2003). When manure was removed every 2-3 days, emissions were reduced by 46%, compared to a weekly removal frequency (Lachance, 2005). Pit recharge with secondary lagoon effluent after weekly or fortnightly emptying reduced emissions by 52% and 63%, respectively, compared to emptying without recharge (Lim et al., 2004). While Ni et al. (1999) observed no relationship between NH_3 emission rate and the manure depth, Ye et al. (2009) reported that a larger space between the slats and the surface of manure in the pit was associated with fewer emissions.

Pit flushing is an efficient mean to reduce NH_3 emissions. Lim et al. (2004) observed significantly reduced NH_3 emissions (-45%) with daily pit flushing compared to static pits. 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 NH_3 volatilization (Monteny, 1996).

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 (Kroodsma et al., 1993; Predicala et al., 2007; Kim et al., 2008a). 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 by separating urine from faeces, however,. 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 (Lachance, 2005). With fattening pigs, reductions of around 50% were achieved by the installation of an under-slat V-shaped scraper (Lachance et al., 2005; Landrain et al., 2009). By increasing the longitudinal slope from 1% to 3%, emissions can be further reduced by 17% (Groenestein, 1994).

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 emissions of around 50% in comparison with conventional storage systems (Kasper et al., 2002; Koger et al., 2002; van Kempen et al., 2003; Lachance, 2005).

The efficiency of the V-shaped scraper and the conveyor belts systems is due to the minimal contact time between urea and faecal microbes and the sequestering of urine. Furthermore, the separation facilitates recycling and treatment of manure, reduces storage requirements and transportation costs, and offers more homogenous materials for land spreading. Nevertheless, increased levels of NH_3 emissions may occur after separation due to extended storage periods (Amon et al., 2006; O'Shea et al., 2009).

With bedded systems, there is little data about the impacts of the removal strategy on NH_3 emissions. With deep litter systems, whereas NH_3 emissions increase regularly throughout the fattening period, principally thanks to accumulation of dejection (Philippe et al., 2007a), the rearing of successive batches on the same litter does not increase the emissions (Nicks et al., 2004). Since the 1990s, straw flow systems have been developed combining straw supply, a sloped floor and frequent manure scraping (Bruce, 1990). With this kind of manure management, Philippe et al. (2007b) observed an important increase of emissions compared to the conventional slatted floor system (13.3 vs. 5.0 g NH_3 pig^{-1} day^{-1}), despite daily scraping and liquid fraction separation. The

rapid development of urease activity on concrete floor (Elzing and Monteny; 1997; Braam and Swierstra, 1999) could explain this result.
In a straw flow system adapted by Amon et al. (2007), the daily scraping does not significantly decrease emissions compared to a dung channel system. These results can be explained by the spreading of faeces and urine over the floor caused by scraping.

In all cases, when slurry or litter is stored outside, weather conditions as temperature and wind speed also impacts on emissions. Therefore, a whole assessment of NH_3 emissions is needed for the entire process, including storage and spreading.

4. Conclusion

Ammonia emissions associated with pig production are important contributors to global emissions. Releases occur inside the pig houses, but also outside during manure storage and spreading. Therefore, complete evaluation of the entire manure management process is needed to really limit emissions and to avoid that the implementation of an efficient mitigation option has potentially negative effect in the next steps.

In pig buildings, significant reduction can be achieved operating on housing conditions and dietary factors.

With regard to the housing conditions, the floor type greatly impacts NH_3 production with differences between slatted floor and bedded floor systems. However, comparisons between the two systems fail to reach a consensus in favour/disfavour of a floor type, principally due to the large number of variants and adaptations that can be met in both systems. With straw-based litter, increasing the amount of straw supply seems a key factor to minimize NH_3 emissions. With slatted floor systems, emissions are lower with smooth materials like cast iron, metal or plastic slats compared to traditional concrete slats. However, welfare, economic or technical concerns can be obstacles for their application.

Partly slatted floors are usually associated to lower NH_3 emissions. However, increased emissions related to the fouling of the solid floor with pig dejections can be observed in case of insufficient area or hot conditions. Reduction of the animal density (especially in last finishing period), increase of the ventilation rate or installation of sprinklers are common means avoiding these obnoxious effects. The location of excretory area by pigs is also influenced by the pen design. In order to reduce NH_3 emissions, slatted floor area would be preferably placed at the back of the pen, away from the feeder and the drinker, with open pen partition in this area.

Several mitigation options were developed regarding the manure removal system. The reduction of the slurry pit surface thanks to sloped pit walls seems related to proportional reduction of NH_3 emissions. Frequent manure removal, flushing and separation of urine from faeces by V-shaped scraper or conveyor belts reduce by about 50% the NH_3 releases from the buildings. However, the complete evaluation of the entire manure management process is needed, including storage, treatment and spreading.

Air scrubber is a very efficient mean to capture NH_3 from the exhaust air. Ammonia removal efficiency up to 90% can be achieved with this system. However, air scrubber is not very economically attractive because of high investment and operational costs. Therefore, researches to improve the cost-efficiency are still needed.

Dietary composition is an important factor that impacts on NH_3 emissions that are highly correlated to the N intake and the feed efficiency. For fattening pigs, reduced emissions can be achieved by improved growth performance thanks to genetic selection or modification of the hormonal status. Immuno-castration, that is expected to become widespread, would impact on outputs and consequently on NH_3 emissions in a way that has not yet been precisely determined. In any case, a closer match between dietary N intakes and requirement of the pigs according to the physiological or growth stage is effective to decrease NH_3 emissions. In this way, diets with reduced CP content are effective in reducing the emissions with almost 10% of reduction for every 10 g kg^{-1} reduction in dietary CP.

Dietary inclusion of NSP reduces NH_3 emissions from slurry by about 40% However, under practical conditions, increased dirtiness of the floor due to the increases of the amount and the viscosity of the faeces could prevent the reduction of NH_3 production. Moreover, the higher CH_4 emissions associated to high fibre diets balance the beneficial effects on NH_3 emissions.

Dietary inclusion of acidifying salts is also effective in decreasing the NH_3 releases. Significant reductions of around 40% were obtained with benzoic acid. Other feed additives like Yucca extract, zeolites, probiotics, humic substance or lactose succeed in significantly reducing NH_3 emissions.

The cost effectiveness of dietary manipulation implemented to lower NH_3 emissions is difficult to evaluate owing to the large fluctuation of raw materials prices. In the current market conditions, reduced CP diet and inclusion of acidifying salts seem effective feeding strategies at relatively low costs.

In conclusion, a large number of mitigation techniques are available to reduce NH_3 emissions from pig houses, whatever the floor type. The evaluation of the housing conditions has to integrate the combination of numerous parameters like ventilation system, manure removal strategy or diet composition. Besides, the choice for a housing system is also influenced by collateral factors, such as the effects on animal health, performance and welfare, the greenhouse gas emissions (CH_4 and N_2O) and surely the investment and operating costs. Specific field conditions will guide decision in favour of mitigation techniques.

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3. GAZ A EFFET DE SERRE ET ELEVAGE DE PORCS

Les émissions de gaz à effet de serre (GES) contribuent aux changements climatiques (IPCC, 2007). Les principaux GES incriminés sont le dioxyde de carbone (CO_2), le méthane (CH_4) et le protoxyde d'azote (N_2O). L'influence d'un gaz sur le réchauffement de la planète dépend de ses propriétés radiatives et de sa durée de vie dans l'atmosphère. La notion d'équivalent CO_2-(Eq-CO_2) permet d'exprimer le potentiel de réchauffement global (PRG) d'un gaz en le comparant à celui du CO_2. Ainsi, le CH_4 et le N_2O ont un PRG qui vaut respectivement 34 et 298 fois celui du CO_2 sur une échelle de temps de 100 ans (IPCC, 2013).

Les activités d'élevage sont responsables de 18% des émissions anthropiques de GES (Steinfeld et al., 2006). Ce secteur est à l'origine de 9% des émissions de CO_2, 37% des émissions de CH_4 et 65% des émissions de N_2O (Steinfeld et al., 2006). Globalement, 43% des émissions sont liées aux cultures destinées à la fabrication d'aliment pour bétail, 31% à la gestion des effluents et 25% aux fermentations entériques, alors que les consommations énergétiques pour le transport et la transformation des produits animaux en représentent moins de 1% (Steinfeld et al., 2006). La production porcine est le deuxième contributeur de GES associés à l'élevage, avec 13% des émissions totales, les ruminants concentrant 79% des émissions et les volailles intervenant pour 8% (FAO, 2013a et 2013b). Les émissions d'Eq-CO_2 associées à la production de viande correspondent respectivement à 49,2, 6,1 et 5,4 kg par kg de carcasse de bovins, de porcs et de volailles (FAO, 2013a et 2013b). Avec l'augmentation de la demande mondiale en viande prévue dans les années à venir, il est essentiel pour les filières animales de réduire leurs émissions de GES afin de garantir leur durabilité.

La synthèse bibliographique présentée ci-après explore les facteurs influençant la production de CO_2, CH_4 et N_2O par les animaux et les effluents au niveau des porcheries et tente d'identifier des moyens de réduction. Ainsi, il ressort de la littérature que les émissions de GES fluctuent essentiellement en fonction du type de logement, du mode de gestion de l'effluent et des caractéristiques de la ration.

Les comparaisons entre élevages sur caillebotis et sur litière semblent mettre en évidence des émissions d'Eq-CO_2 supérieures à partir des seconds, attribuables essentiellement à une augmentation des émissions de N_2O (Robin et al., 1999). Néanmoins, de grandes variations sont observées au sein de chaque système, avec des effets parfois opposés en fonction du gaz émis. Par exemple, l'utilisation d'une litière à base de sciure réduit les émissions de CH_4 mais augmente les émissions de N_2O, en comparaison à une litière à base de paille (Nicks et al., 2004). Des études complémentaires permettraient de préciser les raisons de cette variabilité.

Que les porcs soient élevés sur caillebotis ou sur litière, les émissions de GES sont diminuées par une évacuation fréquente des effluents (Godbout et al., 2006 ; Amon et al., 2007 ; Lagadec et al., 2012). Ces pratiques peuvent être associées à d'autres techniques telles la séparation des phases solide et liquide, ou la biométhanisation, renforçant ainsi la valorisation des effluents et le potentiel de réduction des émissions (Kaparaju et Rintala, 2011).

Concernant l'impact de l'alimentation sur les émissions, les études montrent que la teneur en fibres influence directement la production de CH_4 en stimulant la méthanogenèse aussi bien au niveau de l'intestin des animaux que de l'effluent (Rijnen et al., 2001 ; Le Goff et al., 2002a ; Jarret et al., 2012). Par contre, la réduction du taux de protéines de l'aliment, connue pour diminuer l'excrétion azotée, ne conduit pas à un abattement systématique des émissions de N_2O (Philippe et al., 2006 ; Le et al., 2009 ; Osada et al., 2011). La composition de la ration ne semble pas influencer fortement les émissions directes de CO_2 (Atakora et al., 2005 ; Le et al., 2009).

Dans tous les cas, des conditions d'élevage qui répondent au mieux aux besoins physiologiques des animaux et qui permettent d'optimaliser leur potentiel zootechnique auront des conséquences bénéfiques sur les émissions. La conception des bâtiments, la maîtrise des paramètres bioclimatiques, le contrôle sanitaire du troupeau et la sélection génétique pourront ainsi contribuer à réduire la production de GES à partir des porcheries.

Emissions of carbon dioxide, methane and nitrous oxide by animals and manures in pig buildings

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Keywords

Carbon dioxide – Methane – Nitrous oxide - Pig – Manure

Abstract

Environmental impacts of livestock production are attracting increasing attention, especially the emission of greenhouse gases (GHG). Currently, pork is the most consumed meat product in the world and its production is expected to grow in next decades. This paper deals with the production of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) by animals and manures from pig buildings, with focus the influences of rearing techniques and nutrition. GHG emissions in piggeries originate from animals with CO_2 exhalation and CH_4 enteric fermentation, and from manures with CO_2-, CH_4- and N_2O-releases. CO_2 exhalation ($E\text{-}CO_{2,pig}$) depends on the physiological stage, the body weight (BW), the production level and the feed intakes. Enteric CH_4 ($E\text{-}CH_{4,pig}$) is principally function of the dietary fibre intakes and the fermentative capacity of the pigs'hindgut. The following equations are proposed to estimate $E\text{-}CO_{2,pig}$ (in kg day^{-1}) and $E\text{-}CH_{4,\,pig}$ (in g day^{-1}) for fattening pigs: $E\text{-}CO_{2,pig} = 0.136 \times BW^{0.573}$; $E\text{-}CH_{4,\,pig} = 0.012 \times dRes$; with BW (in kg) and dRes for digestible residues (in g day^{-1}). Numerous pathways are responsible for GHG production in manure. In addition, microbial, physical and chemical properties of the manure interact together and modulate the level of emissions. Influencing factors for both liquid and solid systems have been investigated. A large range of parameters impacting the level of GHG production from pig houses were reported but few of them can be considered indubitably as mitigation techniques because some strategies show contradictory effects depending on the gas, the circumstances and the study. However, frequent manure removal seems efficient to reduce concurrently CO_2-, CH_4- and N_2O-emissions from buildings for both slatted and bedded floor systems. Manure removal operations may be associated with specific storage condition and efficient treatment to further reduce

emissions. Several feeding strategies were tested to decrease GHG emissions but they seem inefficient to reduce emissions significantly and durably. Anyway, good management practices that enhance zootechnical performance will have beneficial consequences on GHG emissions intensity. GHG emissions from pig houses are estimated to 448.3 kg CO_2eq per slaughter pig produced or 4.87 kg CO_2eq per kg carcass, taken into account CO_2-, CH_4 and N_2O-production from animal and manure in pig houses. Fattening period accounts for more than 70% of total emissions while gestation, lactation and weaning periods contribute each to about 10% of total emissions. Emissions of CO_2, CH_4 and N_2O contribute to 81, 17 and 2% of total emissions from buildings, representing 3.87, 0.83 and 0.11 kg CO_2eq per kg carcass, respectively.

1. Introduction

Pork is currently the most widely consumed meat product in the world, accounting for 38% of total meat consumption (Table 1; FAO, 2011). By 2050, worldwide pork consumption is expected to increase by almost 40% owing to the demographic growth, the changes in food preferences and the agricultural intensification (FAO, 2011). Increasing meat consumption makes the environmental impacts of livestock production a crucial issue, especially the effects on air pollution and consequently climate change (Steinfield, 2006).

Table 1 – Projected human population (in billion people) and global meat consumption (in million tons) from 2010 to 2050 (adapted from FAO, 2011)

	2010	2020	2030	2050	Growth 2010 to 2050
Human population	6.91	7.67	8.31	9.15	+32%
Meat consumption					
Pig meat	102.3 (38%)	115.3 (36%)	129.9 (34%)	140.7 (30%)	+38%
Poultry meat	85.9 (32%)	111.0 (35%)	143.5 (38%)	193.3 (42%)	+125%
Bovine meat	67.3 (25%)	77.3 (24%)	88.9 (23%)	106.3 (23%)	+58%
Sheep/goat meat	13.2 (5%)	15.7 (5%)	18.5 (5%)	23.5 (5%)	+78%
All meat	268.7 (100%)	319.3 (100%)	380.8 (100%)	463.8 (100%)	+73%

It is widely recognized that increases in the concentrations of greenhouse gases (GHG) in the atmosphere may cause global warming. International regulations aim to drastically reduce GHG emissions. The principal gases involved in this process include carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Cumulated emissions of GHG can be expressed in CO_2-equivalents (CO_2eq) taken into account their global warming potentials (GWP). The GWP of CH_4 and N_2O over a 100-year period are evaluated to 25 and 298 times that of CO_2, respectively (IPCC, 2007).

Globally, livestock production account for 18% of anthropogenic emissions of GHG (Steinfeld et al., 2006). Pig production is the second contributor after cattle, with about 13% of total emissions related to livestock (Table 2; FAO, 2011). GHG emissions intensity of meat production is estimated to 49.2, 21.0, 6.1, 5.4 kg CO2eq per kg of carcass for cattle, sheep/goat, pig and poultry, respectively (FAO, 2013a and 2013b). Thus, GHG emissions associated with pig production could be considered rather low. Nevertheless, some mitigation options could be applied in this sector to effectively reduce global emissions.

Table 2 – Contribution of livestock species to global greenhouse gas emissions (adapted from FAO, 2006; FAO, 2013a and 2013b).

Species	**Greenhouse gases emissions (million tons CO_2eq year^{-1})**			
	CO_2 emissions	**CH_4 emissions**	**N_2O emissions**	**Total emissions**
Cattle	1166.2 (61%)	2072.8 (81%)	661.6 (60%)	3900.6 (70%)
Small ruminants	69.9 (4%)	244.5 (10%)	202.6 (18%)	517.0 (9%)
Pigs	338.9 (18%)	237.3 (9%)	131.1 (12%)	707.3 (13%)
Poultry	332.2 (17%)	-	107.3 (10%)	439.5 (8%)
Total	1907.2 (100%)	2554.5 (100%)	1102.6 (100%)	5564.3 (100%)

CO_2eq : Emissions of CO_2-equivalents, including CO_2, CH_4 and N_2O, taken into account global warming potentials of 25 and 298 for CH_4 and N_2O, respectively.

This paper deals with the production of CO_2, CH_4 and N_2O by animals and manures from pig buildings. Attention is paid to the influence of rearing techniques and nutrition on the level of emissions. Emissions associated to feed production, land use and land use change, energy consumption, manure spreading, transportation and food processing were not included in this discussion. Emissions associated to outside manure storage and manure treatments are also out of the scope of this review but they will be slightly addressed due to the link with emissions from the buildings. Direct CO_2 emissions by animals and manures are usually excluded from GHG assessment because it is assumed that they are compensated by CO_2 consumption by photosynthesis of plants used as feed. However, these CO_2 emissions at house level are not negligible and might differ from one rearing system to another (Philippe et al., 2007a and 2007b). Thus, option was taken to study their influencing factors in order to identify potential ways of reduction.

This review describes the processes that are responsible of production of CO_2, CH_4 and N_2O by animals and manures at pig house level, study the effects of rearing conditions and dietary factors on emissions, point out some mitigation techniques and finally estimate total GHG emissions from pig buildings.

2. Sources of emissions

2.1. Carbon dioxide

The emissions of CO_2 from pig houses come from two sources: the exhalation by pigs and the releases from manure.

2.1.1. Exhalation by pigs

The CO_2 production during the respiration is related to the respiratory quotient, defined as the ratio between the volume of CO_2 production and the volume of oxygen consumption. In practice, the respiratory quotients reported in the literature are around 1.10 for growing pigs, around 1.00 for piglets and around 0.90 for reproductive sows (Moehn et al., 2004; Pedersen et al., 2008; Atakora et al., 2011b). CO_2 exhalation can also be derived from the animal heat production (HP). Under thermoneutral conditions, HP corresponds to the energy used for maintenance and the fraction of the ingested metabolisable energy which is not retained for production (growth or milk production). Below thermoneutrality, energy used for thermoregulation has to be included (Noblet et al., 1989). The International Commission of Agricultural Engineering (CIGR, 2002) proposed an estimation of HP at thermoneutrality based on body weight, production level and feed energy intake. The models were:

For gestating sows:

$$HP = 4.85\ BW^{0.75} + 8\ \times 10^{-5}\ p^3 + 76\ Y_1\ , (1)$$

For lactating sows (including piglets):

$$HP = 4.85\ BW^{0.75} + 28\ Y_2\ , (2)$$

For piglets (up to 20 kg):

$$HP = 7.4\ BW^{0.66} + \ [1 - (0.47 + 0.003\ BW)]\ \times\ (n\ \times 7.4\ BW^{0.66} -\ 7.4\ BW^{0.66}), (3)$$

For fattening pigs (from 20 to 120 kg):

$$HP = 5.09\ BW^{0.75} + \ [1 - (0.47 + 0.003\ BW)]\ \times\ (n\ \times 5.09\ BW^{0.75} -\ 5.09\ BW^{0.75}), (4)$$

with HP, in W; BW for body weight, in kg; p for day of pregnancy; Y_1 for weight gain, in kg per day, Y_2 for milk production, in kg per day; and n, coefficient used to express feed energy intake function of maintenance requirements, ranging from 4.01 to 3.44 for piglets weighting 2 to 20 kg and from 3.44 to 2.14 for fattening pigs weighting 20 to 120 kg (Brown-Brandl et al., 2004; Pedersen et al., 2008). In order to convert HP into CO_2 exhalation, factors were proposed for fattening pigs, piglets and reproductive sows, i.e. 0.185, 0.170 and 0.165 L h^{-1} per W, respectively. By example, for fattening pigs, massic CO_2 exhalation, E-$CO_{2,\,pig}$ expressed in kg d^{-1}, can be calculated as follow:

$$E - CO_{2,pig} = 24 \times \frac{44}{22.4} \times 10^{-3} \times 0.185 \times HP, (5).$$

Other experiments were carried out to measure or estimate CO_2 exhalation from practical parameters. Models developed for fattening pigs were described below and illustrated on Figure 1. Müller and Schneider (1985) established a model by keeping pigs in metabolic crates from 20 to 110 kg and estimated the CO_2 exhalation by the following equation:

$$E - CO_{2,pig} = 0.114\, BW^{0.588}, (6).$$

Feddes and DeShazer (1988) elaborated a model taken into account feed quantity, feed quality, respiratory quotient and efficiency of energy utilization. Finally, authors proposed a conversion factor of 306 L of CO_2 per kg of feed consumed (FI, in kg d-1), for growing pigs. The feed intake can be estimated from the BW by equation derived from the data of Aubry et al. (2004). Thus, CO_2 exhalation is calculated by the following equation:

$$E - CO_{2,pig} = 306 \times \left({}^{44}/_{22.4}\right) \times 10^{-3} \times 0.227\, BW^{0.549}, (7).$$

van 't Klooster and Heitlager (1994) developed a model to predict CO_2 exhalation, as function of pig weight, feed intake and metabolisable energy content in feed. Since feed intake can be derived from the pig weight (Aubry et al., 2004) and energy content of feed is a constant, estimated to 12.9 MJ kg^{-1}, the model can be simplified as follow:

$$E - CO_{2,pig} = 2.88 \times 10^{-2} \times BW^{0.75} + 8.29 \times 10^{-2} \times BW^{0.549}, (8).$$

Ni et al. (1999a) investigated CO_2 exhalation for pigs from 32 to 105 kg kept in a commercial fattening house. Field measurements showed that the daily mean CO_2 exhalation was about 10% higher than the tranquil CO_2 exhalation rate defined as the CO_2 exhaled by pig respiration when the animal was in tranquil condition during the course of a day. Thus, a model was built to predict E-$CO_{2,\,pig}$ from the BW:

$$E - CO_{2,pig} = 1.1 \times 24 \times 8.489\, BW^{0.46}, (9).$$

Brown-Brandl et al. (2004) collected literature data on swine heat production and presented a model that allows estimating CO_2 exhalation from BW:

$$E - CO_{2,pig} = 0.185 \times 0.665\ BW^{0.62}, (10).$$

Similarly, Pedersen et al. (2008) reviewed numerous experiment conducted in metabolism crates and proposed the following model compiling the results obtained with pigs from 20 to 120 kg:

$$E - CO_{2,pig} = 0.0998\ BW^{0.646}, (11).$$

By combining the data from the reported models (equations 4 to 11), a synthetic model can be proposed to predict CO_2 exhalation for pigs from 20 to 120 kg BW (Figure 1; R^2= 0.91):

$$E - CO_{2,pig} = 0.136\ BW^{0.573}, (12).$$

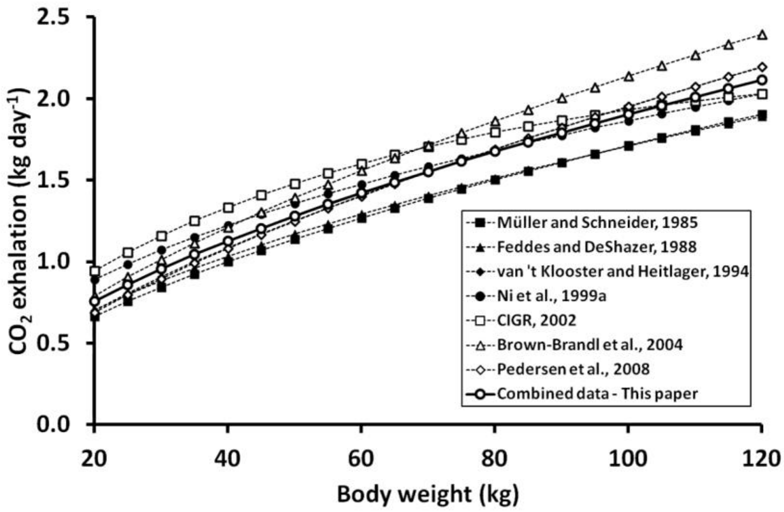

Figure 1 - Carbon dioxide (CO_2) exhalation by pigs estimated as a function of the body weight

Based on equations 1, 2, 3 and 12 and taken into account usual productive performance, respiratory CO_2-production can be estimated to 2.23, 3.68, 0.88 and 1.55 kg CO_2 head^{-1} day^{-1} for gestating sows, lactating sows, weaned piglets and fattening pigs, respectively.

Outside thermoneutrality, ambient temperature impacts on HP and thus CO_2 exhalation. HP increases at lower temperatures and decreases at higher temperatures. With fattening pigs, Quiniou et al. (2001) observed a decrease in HP of 1.2% per °C for temperature range from 12° to 29°C, and Huynh et al. (2007) observed a decrease of 0.6% per °C for temperature range from 16 to 32°C. For piglets around 25 kg BW, Collin et al. (2001) reported a decrease in HP of 2.2% per °C for temperature of 23 and 33°C.

These corrective factors can be used for CO_2 calculation under temperature outside thermoneutrality.

CO_2 exhalation is also influenced by the diurnal variation of animal activity. Indeed, Ni et al. (1999a) observed that CO_2 exhalation rate can be as high as 200% of the tranquil condition when pigs were very active during daytime. In the literature, correlation coefficients between CO_2 production and animal activity range from 0.55 to 0.89 (Pedersen and Rom, 1998; Delcourt et al., 2001; Jeppsson, 2002; Ngwabie et al., 2011). Actually, the highest emission rates are observed during the feeding time (van Milgen et al., 1997; Moehn et al., 2004). Typically, the diurnal pattern of activity and CO_2 emissions for fattening pigs fed ad libitum consists in a first peak in the morning and a second peak in the afternoon, corresponding to feeding behaviours (Figure 2, Philippe et al., 2013b). Thus, modifications of the feeding schedule impacts the diurnal pattern of animal activity and CO_2 emissions. By example, delaying the second meal of gestating sows fed twice a day from 15:30 to 21:30 induces a significant reduction of diurnal mean activity (Groensetein et al., 2003). Similarly, sows fed with an electronic feeder were less active if the feeding started in the afternoon instead of in the morning (Groensetein et al., 2003). Thus, management techniques and housing conditions that reduce pig activity could also diminish the level of CO_2-exhalation.

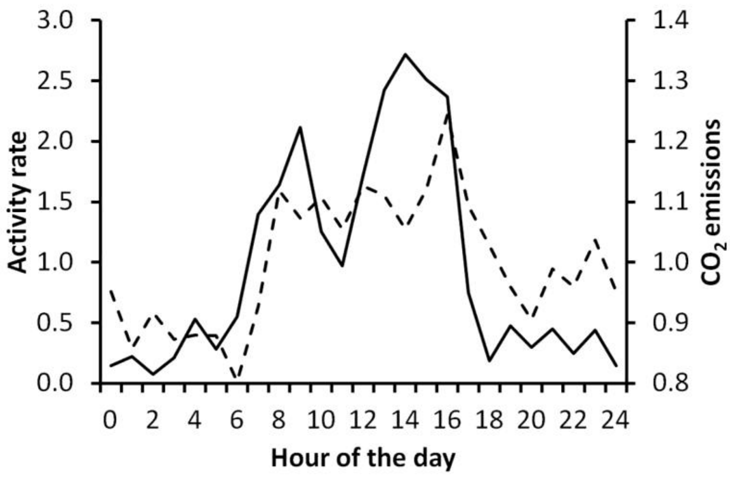

Figure 2 - Nycthemeral evolution around the daily mean (value=1) of the activity rate of pigs (defined as the proportion of standing pigs, plain line) and the carbon dioxide emissions (CO_2, dashed line) associated to fattening pigs kept on slatted floor (adapted from Philippe et al., 2013)

Compared to other species, pigs present intermediate value regarding CO_2-exhalation (Table 3; FAO, 2006). Expressed per livestock unit (LU, equals to 500 kg BW), pigs produce 8.71 kg CO_2 day^{-1} by respiration while poultry and small ruminants are associated with extreme values, i.e. 2.53 and 14.89 kg CO_2 day^{-1}, respectively. Cattle and horses emit on average 5.2 kg CO_2 day^{-1} due to respiration.

Table 3 –Emissions of carbon dioxide (CO_2) from respiration as influenced by the species (adapted from FAO, 2006)

Species	kg CO_2 $head^{-1}$ day^{-1}	kg CO_2 LU^{-1} day^{-1}
Cattle	3.49	5.21
Horses	3.54	5.23
Pigs	1.73	8.71
Poultry	0.01	2.53
Small ruminants	0.79	14.89

LU: equals to 500 kg of body weight

2.1.2. Release from manure

For a long time, CO_2 emissions from manure were believed negligible (Anderson et al., 1987; van 't Klooster and Heitlager, 1994). According to some recent research, releases from manure were estimated at 4-5% of the CO_2 exhaled by animals (CIGR, 2002; De Sousa et al., 2004; Dong et al., 2007). Some authors reported higher CO_2 release accounted for 10 to 30% of the respiratory production (Jeppsson, 2000 and 2002; Philippe et al., 2007a and 2007b; Pedersen et al., 2008; Philippe et al., 2012a). During an experiment carried out in a commercial fattening unit emptied or filled with pig, emissions from manure were evaluated around 40% of the tranquil CO_2 exhalation rate (Ni et al., 1999b). Anyway, the production from manure has to be taken into account, even though it is not the main source of CO_2 in pig houses.

In the manure CO_2 originates from three sources: (1) the rapid hydrolysis of urea into NH_3 and CO_2 catalysed by the enzyme urease; (2) the anaerobic fermentation of organic matter into intermediate volatile fatty acids (VFA), CH_4 and CO_2; (3) the aerobic degradation of organic matter (Jeppsson, 2000; Moller et al., 2004; Wolter et al., 2004). For liquid manures, the anaerobic processes were frequently considered as the main source of CO_2 (Ni et al., 1999b). However, this statement is contradictory to the results of Moller et al. (2004) who observed under laboratory conditions that the aerobic and anaerobic processes are almost of equal importance at temperature of 20°C while lower temperature (15°C) favoured the aerobic process. Anyway, total emissions increase with temperature, as a consequence of the thermal effect on physical, chemical and microbiological processes. For instance, higher CO_2 emissions (+28%) were observed when the slurry was stored at 25°C rather than 5°C (Dinuccio et al., 2008). Reduction of CO_2 production (-56%) was obtained by dilution thanks to a reduction of the dry matter content by 54% (Ni et al., 2010). Inversely, mixing slurry with wood shavings (mass ratio of manure to wood shavings 13:1) promotes CO_2 emissions (5.09 versus 2.44 g h^{-1} m^{-2}), as a consequence of increased dry matter content (24.4 versus 18.5%) (Ngwabie et al., 2010).

For solid manures, the principal origin of CO_2 is the aerobic production, so-called composting process, performed by a mesophilic/thermophilic microbial community that convert degradable organic matter (Hellmann et al., 1997; Wolter et al., 2004). The composting process is influenced by several factors like temperature, moisture content, carbon/nitrogen ratio, degradability of carbon compounds, pH level and the physical structure of the organic material (Andersson, 1996; Jeppsson, 2000; Paillat et al., 2005). By example, experiments have shown that CO_2 production was optimized with C/N ratio around 15-20, moisture content around 70% and aeration rate around 0.5 L per min^{-1} kg^{-1} OM (Jiang et al., 2011; Guo et al., 2012). The nature of the substrates also impacts on the level of production, since different bedding materials in the litter create different conditions for the microorganisms (Jeppsson, 2000). Besides, results from barn experiments suggested that the level of CO_2 production is greater from litter than slurry, with emissions increased by 10 to 25% at house level (Philippe et al., 2007a; Pedersen et al., 2008; Cabaraux et al., 2009; Philippe et al., 2011a). However, the influence of the litter on pig activity and related CO_2-production may also contribute to these higher emissions.

2.2. Methane

Methane originates from the anaerobic degradation of organic matter performed by bacteria in the digestive tract of the pigs and in the manure.

2.2.1. Enteric fermentation

The level of enteric CH_4 depends on the diet composition and the fermentative capacity of the hindgut, as measured in metabolic cages by several authors. Thus, CH_4 production by pigs increases linearly with increasing dietary fibre content. In pig production, fibrous diets are usually given to gestating sows to prevent aggressive behaviours related to feed restriction, and to growing pigs to strengthen the gut health around weaning (Philippe et al., 2008) Comparing different diets for fattening pigs with increasing level of sugar beet pulp (SBP) as source of fibres, Rijnen et al., (2001) observed linear increase of emissions from 3.7 g CH_4 pig^{-1} day^{-1} with 0% SBP to 8.0 g CH_4 pig^{-1} day^{-1} with 30% SBP. The botanical origin, the solubility and the fermentability of the fibres also influence the level of production (Philippe et al., 2008). By example, sows fed different diets with similar dietary fibres content but various source of fibres produced significantly more CH_4 in case of incorporation of maize bran compared to wheat bran (7.6 versus 5.1 g CH_4 sow^{-1} day^{-1}; Le Goff et al., 2002b). Indeed, soluble fibres like in maize bran, sugar beet pulp or potato pulp, have higher digestibility and fermentability than insoluble fibres like wheat bran, pea hulls or seed residues (Jorgensen et al., 2007). Several experiments have also showed that the digestive capacity and the fermentative capacity of the pigs depend on the body weight and the physiological stage. With equal amount of ingested fibres, finishing pigs (mean BW: 76 kg) produced 50% more CH_4 than growing pigs (mean BW: 42 kg; Le Goff et al., 2002a). For ad libitum fed pigs, CH_4 production increased by 78% from 60 to 90 kg BW (Ji et al., 2011), and by 33% from 105 to 160 kg BW (Galassi et al., 2005). Likewise, adult sows have greater ability to degrade dietary fibre than fattening pigs, with higher CH_4 production as consequence. For instance, the digestibility coefficient of dietary fibres from maize bran is 0.64 for adult sows compared to 0.44 for fattening pigs (Le Goff et al., 2002c). Greater enteric production by sows can be explained by several factors including increased feeding capacity, better intrinsic ability of bacterial flora to digest fibre, greater number of bacteria, reduction of relative feeding level, and increased transit time (Le Goff et al., 2002c).

Figure 3 illustrates the production of enteric CH_4 for fattening pigs and adult sows reported in the literature as a function of the fibres intake, so-called digestible residues (dRes) as proposed in INRA-AFZ-INAPG (2004) and defined as the difference between digested OM and digested protein, fat, starch and sugar. By compiling these data, the following equations have been developed to predict the CH_4 enteric production ($E\text{-}CH_{4,\,pig/sow}$, in g CH_4 day^{-1}) from dRes intakes (g day^{-1}) for fattening pigs (equation 13) and for adult sows (equation 14):

$$E - CH_{4,pig} = 0.012 \times dRes \; (R^2 = 0.77) (13);$$

$$E - CH_{4,sow} = 0.021 \times dRes \; (R^2 = 0.90) (14).$$

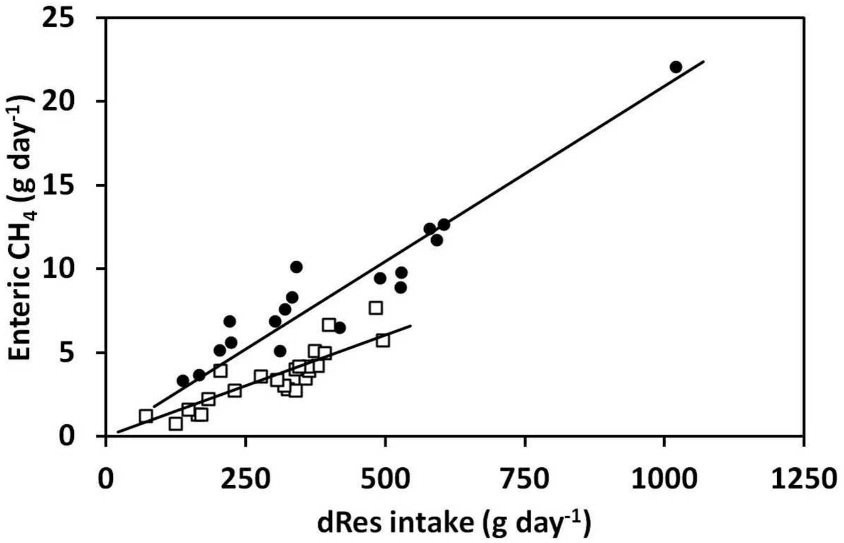

Figure 3 - Estimations of enteric methane (CH_4) production by adult sows (black circles) and fattening pigs (open squares) as a function of the intake of digestive residues (dRes, defined as the difference between digested organic matter and digested protein, fat, starch and sugar) (from Noblet et al., 1994; Jorgensen et al., 1996; Olesen et al., 2001; Le Goff et al., 2002a and 2002b; Ramonet et al., 2002b; Galassi et al., 2004 and 2005; Jorgensen, 2007; Jorgensen et al., 2007; Serena et al., 2008)

By example, the ingestion of 300 g of dRes is associated to the enteric production of 3.6 g CH_4 by fattening pigs and 6.3 g CH_4 by adult sows. Enteric emissions representing energy losses of 56.65 kJ per g of CH_4 produced, it represent about 0.4-0.5% of digestible energy (DE) for fattening pigs and 1.0-1.5% DE for adult sows. According to the tier 1 methodology from IPCC guidelines for national inventories (IPCC, 2006), enteric CH_4 is estimated to 1.5 kg per head per year, corresponding to 4.1 g CH_4 day^{-1}, whatever the diet composition and the physiological stage. Taken into account conventional diet composition and zootechnical performance, Vermorel et al. (2008) estimated for French production the daily enteric CH_4 emissions to 0.8, 2.4 and 8.2 g CH_4 head^{-1} for weaned piglets, fattening pigs and gestating sows, respectively. Corresponding values for German production were proposed by Dämmgen et al. (2012) with 0.9, 2.5 and 6.1 g CH_4, respectively. Comparison of enteric CH_4 production between different species is presented on Table 4. The emission factor associated to pig production was substantially lower than other livestock species. Globally, cattle CH_4 emissions are estimated to 186.6 g CH_4 head^{-1} day^{-1} (corresponding to 202.8 g CH_4 LU^{-1} day^{-1}), while swine CH_4 emissions are estimated to 2.2 g CH_4 head^{-1} day^{-1} (corresponding to 11.1 g CH_4 LU^{-1} day^{-1}). Enteric production by poultry are usually considered negligible (IPCC, 2006).

Table 4 –Emissions of methane from enteric production as influenced by the species (adapted from FAO, 2006; Vermorel et al., 2008)

Species	g CH_4 head^{-1} day^{-1}	g CH_4 LU^{-1} day^{-1}
Cattle	186.6	278.6
Horses	56.7	83.8
Pigs	2.2	11.1
Small ruminants	21.2	399.8

LU: equals to 500 kg of body weight

2.2.2. Release from manure

The releases of CH_4 from manure originate from the temporal succession of microbial processes (Hellmann et al., 1997; Monteny et al., 2006). Initially, unspecified bacteria convert easily degradable substrates into VFA, CO_2 and H_2. This extensive microbial activity increases the temperature and provides suitable conditions for methanogenic bacteria that convert acetate, CO_2 and H_2 into methane under thermophilic environment. Factors that favour CH_4 production are high temperature, lack of oxygen, high level of degradable organic matter, high moisture content, low redox potential, neutral pH, and C/N ratio between 15 and 30 (Moller et al., 2004; Amon et al., 2006; Kebreab et al., 2006). By example, when the storage temperature increased from 15 to 20°C, the CH_4 emissions increased by 42% (Moller et al., 2004). On the contrary, the production is inhibited under aerobic conditions and high concentration of ammonium, VFA and sulphides which inhibit the growth of methanogenic bacteria (Monteny et al., 2006; Vedrenne et al., 2008; Cerisuelo et al., 2012). Addition of clay minerals or zeolites has shown to reduce the toxic effect of ammonia and thus to increase CH_4 production (Hansen et al., 1999; Kotsopoulos et al., 2008). CH_4 emissions can be reduced due to oxidation into CO_2 by methanotrophic bacteria that use CH_4 as source of carbon and energy under aerobic conditions. This process can occur during the passage of CH_4 through crust at the slurry surface or through porous areas within solid manure. The contribution of the manure to the total CH_4 emissions in animal houses is estimated to 70% for the slurry-based systems and to 50% for the litter based systems (Freibauer, 2003). The strictly anaerobic conditions in the slurry explain the higher emissions. Nevertheless, higher temperatures and C/N ratio of the litters also favour methanogenesis from bedded systems but with variable levels of emissions function of litter management.

According to the guidelines for National Greenhouse Gas Inventories (IPCC, 2006), the CH_4 emissions from manure ($E\text{-}CH_{4,\ manure}$, in m^3) can be estimated based on the amount of excreted volatile solid (VS) or organic matter (OM), in kg; the ultimate CH_4 potential (B_0), in m^3 CH_4 per kg VS or OM; and the methane conversion factor (MCF), in%:

$$E - CH_{4,manure} = VS \times B_0 \times MCF \ (15).$$

The IPCC (2006) recommend some values for VS, B0 and MCF, function of the region of the world, the climate, the livestock categories and the type of manure. In Western Europe, the recommended value for VS is 0.30 kg pig^{-1} day^{-1} (IPCC, 2006). In the literature, the B_0 values vary from 0.29 to 0.53 m^3 per kg VS or OM (Moller et al., 2004; Chae et al., 2008; Vedrenne et al., 2008; Jarret et al., 2011; Dämmgen et al., 2012b). The B_0 value proposed by IPCC (2006) is 0.45 m^3 per kg VS. The MCF values recommended for Western Europe under temperate climate (20°C) for fattening pigs are similar for both liquid and solid manure but differ regarding the inside manure storage duration. Thus, factors are 3% and 42% when the manure remains in the building less or more than one month, respectively (IPCC, 2006). It represents 7.4 and 104.0 g CH_4 pig^{-1} day^{-1}, respectively. In literature, extreme MCF values range from 2% to 80% function of the manure type, the manure management, the storage duration, the diet composition and the temperature (Moller et al., 2004; Jarret et al.; 2011; Dämmgen et al., 2012b; Rodhe et al., 2012). During long-term storage (90 days), the slurry MCF value increased from 5.3 to 31.3% at temperature ranging from 15 to 20 °C, respectively. At high temperature, reducing the storage duration from 90 to 30 days decreases the MCF to 10.9% (Moller et al., 2004). Taken into account the proportion of manure management system usage, the emission factor for releases from swine manure in temperate Western Europe is estimated to 12 kg CH_4 $head^{-1}$ $year^{-1}$, or 32.9 g CH_4 day^{-1}, including inside and outside storage (IPCC, 2006).

2.3. Nitrous oxide

In pig houses, N_2O only originates from the manure. Its formation mainly occurs during incomplete nitrification/denitrification processes performed by micro-organisms that normally convert NH_3 into non-polluting diazote (N_2). N_2O can be also produced during an abiotic ammonium conversion under acidic conditions, so-called chemo-denitrification (Oenema et al., 2005; Petersen and Miller, 2006). The main microbial pathways involved in the N_2O synthesis are presented in the Figure 4.

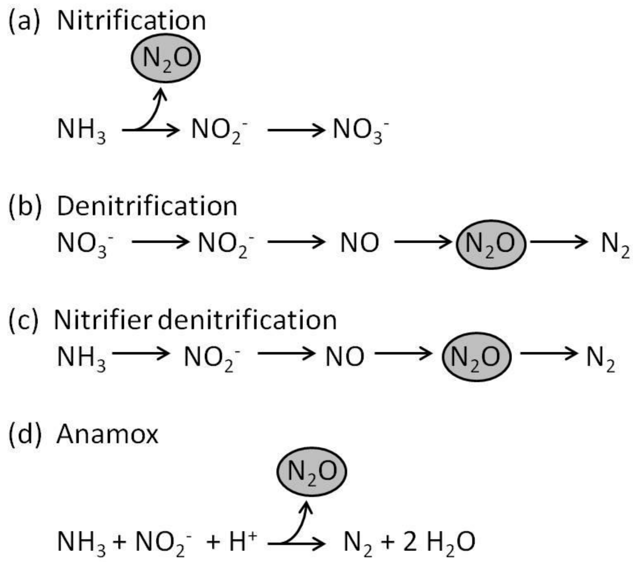

Figure 4 - Microbial pathways involved in the N_2O synthesis in manure

Nitrification is composed of two steps, nitritation and nitratation, and is performed by bacteria with the prefix *Nitroso* (*Nitrosomonas* for example). Nitritation is the oxidation of ammonia into hydroxylamine (NH_2OH) that is then oxidised into nitrite (NO_2^-) (equation 16):

$$NH_3 + {}^3/_2\ O_2 \rightarrow NH_2OH \rightarrow NO_2^- + H^+ + H_2O, (16)$$

Nitratation is performed by bacteria with the prefix *Nitro* (*Nitrobacter* for example). It consists in the oxidation of NO_2^- into nitrate (NO_3^-):

$$NO_2^- + {}^3/_2\ O_2 \rightarrow NO_3^-, (17)$$

Nitrification is usually carried out by autotrophic bacteria that require aerobic conditions with pH value above 5 (Kebreab et al., 2006). During nitrification, N_2O is synthesized when there is a lack of oxygen and/or a nitrite accumulation.

Denitrification is the reduction of NO_3^- into N_2, with many intermediate compounds produced (NO_2^-, nitric oxide (NO), and N_2O). In manure, denitrification is principally performed by heterotrophic facultative aerobic bacteria that use NO_3^- as an electron acceptor when there is little oxygen in anoxic conditions. Denitrification requires a source of easily biodegradable organic carbon as reductans (Kebreab et al., 2006; Girard et al., 2009). The equation 18 presents the denitrification reaction with acetic acid (CH_3COOH) as carbon source:

$$8\ NO_3^- + 5\ CH_3COOH \rightarrow 4\ N_2 + 10\ CO_2 + 6\ H_2O + 8\ OH^-, (18)$$

During denitrification, N_2O production is promoted in the presence of oxygen and/or low availability of degradable carbohydrates (Poth and Focht, 1985; Driemer and Van den Weghe, 1997).

N_2O can be also formed during other microbial pathways: the ammonium oxidation under aerobic or anaerobic conditions, so-called nitrifier denitrification and anamox, respectively. Most of nitrifying and denitrifying microorganisms are mesophilic and thus the N_2O formation is generally inhibited by temperature above 40-50°C (Hellmann et al., 1997; Kebreab et al., 2006). However, some authors have detected N_2O synthesis under thermophilic conditions (Wolter et al., 2004; Szanto et al., 2007).

The relative contribution of these numerous 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.

The guidelines for National Greenhouse Gas Inventories (IPCC, 2006) recommend estimating the direct N_2O emissions by multiplying N excreted by animals (N_{ex}) by a specific factor for each type of manure management system. By example, this factor is 0.2% N_{ex} for pit storage under animals and 1% N_{ex} for deep bedding. Assuming 40 g N_{ex} pig^{-1} day^{-1}, it represents 0.13 and 0.63 g N_2O pig^{-1} day^{-1}, respectively. Higher values were reported in the literature, especially for bedded systems for which emissions can amount up to 20% N_{ex} (Groenestein et al., 1996; Hassouna et al., 2005; Philippe et al., 2007a; Philippe et al., 2011a; Vandré et al., 2013).

3. Influencing factors

The GHG emissions from pig houses are principally influenced by the floor type, the manure management and the nutrition. The climatic conditions inside the building also impact the emissions.

3.1. Climatic conditions

Gaseous emissions are positively related to ambient temperature and ventilation rate. By example, CH_4 emissions were doubled when the indoor temperature in a fattening pig unit increased from 16.8 to 22.8°C (Ngwabie et al., 2011). In a commercial pig house emptied of pigs, Ye et al. (2011) observed CO_2 emissions shifting from 2.95 to 7.57 g CO_2 h^{-1} per m^2 of slurry for ventilation rate ranging from 211 to 1852 m^3 h^{-1}, as a consequence of higher air exchange rate at slurry surface. With similar experimental design, Ni et al. (1999b) measured emissions increasing from 0.8 to 25.8 g CO_2 h^{-1} per m^2 of slurry for ventilation rate ranging from 160 to 3350 m^3 h^{-1}. The location of the fans also contribute to modulate the emissions. Air inlets or outlets located near the manure surface increase the emissions due to greater air flow at interface (Hayes et al., 2006). Anyway, using climate conditions to modulate the releases of GHG seems rather unpractical since the ambient parameters must primarily respect the physiological needs of the animals. Nevertheless, optimization of the heating and the ventilation in the housing system can have beneficial effects on emissions. Good practices include insulation of the building, adaptation to internal (like animal type and density) and external factors (like season and weather), management of air circulation and regular monitoring of the devices. Regulation of climatic parameters has also influence on health, performance, welfare and behaviour of the pigs with indirect effects on the level of emissions. In addition, energy saving related to optimal management of climatic factors can be considered environmentally and economically beneficial.

3.2. Floor type and manure management

In pig production, the most frequent housing conditions are based on slatted floor with a deep pit underneath for the storage of the slurry. Besides this traditional system, bedded systems have met renewed interest during last decades, as they are related to improved welfare, reduced odour nuisance and a better brand image of livestock production. For both housing system, a large range of parameters may influence the GHG emissions.

3.2.1. Slatted floor systems

It is usually assumed that the emission of pollutant gases can be reduced by lowering the slurry emitting surface. With implementation of partly slatted floor, some authors observed reduction in CO_2 production by 7 to 13% compared to fully slatted floor, whereas slurry is not the main source of emission (Table 5; Sun et al., 2008; Guingand et al., 2010). For CH_4 production, contradictory results were reported in literature, with decreased emissions (Lägue et al., 2004; Philippe et al., 2014) or increased emissions associated with partly slatted floor (Guingand et al., 2010). The effect of the slatted floor area on N_2O emissions shows also conflicting results (Fitamant et al., 1999; Lägue et al., 2004; Guingand et al., 2010; Philippe et al; 2014). Nevertheless, absolute N_2O emissions from slurries remained quite low whatever the type of slatted floor. Globally, cumulated emissions of GHG, expressed in CO_2-equivalent (CO_2eq, taken into account global warming potential of 25 and 298 for CH_4 and N_2O, respectively) are reduced by 4 to 13% by the application of partly slatted floor compared to fully slatted floor.

The increase of the slurry level consequently to the reduced pit capacity could favour emissions since a smaller space between the slats and the surface of manure was suggested to increase the gases releases (Ye et al., 2009). However, several authors reported that higher slurry depth does not promote gas releases (Lägue et al., 2004; Haeussermann et al., 2006; Ye et al., 2011).

Frequent manure removal has been proposed to diminish the emissions from the building. Total emissions including outside storage will be also reduced provided lower outside temperature than inside or specific manure treatments. A weekly discharge reduced CH_4 and N_2O 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 CH_4 emissions reduced by 19%, but doubled N_2O emissions. Yet, cumulated emissions (expressed in CO_2-Eq) are lowered by 16%. When manure was removed 3 times a week in place of once, CH_4 emissions were reduced by 16% and N_2O emissions remained insignificant (Lavoie et al., 2006). Anyway, CO_2 emissions seem not impacted by the removal frequency (Osada et al., 1998; Guarino et al., 2003; Lavoie et al., 2006).

Pit flushing is also an efficient mean to mitigate emissions. Sommer et al. (2004) estimated to 35% the reduction potential of cumulated GHG (CH_4 and N_2O) with daily flushing compared to static pit. By combining frequent flushing (6 times a day) and reduced slurry surface, Lagadec et al. (2012) measured cumulated emissions reduced by 35% with manure gutters and by 55% with flushing tube, compared to static pit. Frequency, duration and pressure of the flushing water also impacted on the efficiency of mitigations (Kroodsma et al., 1993). 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).

Table 5 – Effect of the proportion of slatted floor (fully or partly slatted floor) on emissions (pig^{-1} day^{-1}) of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CO_2-equivalent (CO_2eq, including CO_2, CH_4 and N_2O and taken into account global warming potentials of 25 and 298 for CH_4 and N_2O, respectively) associated to fattening pigs

References	Fully slatted floor				Partly slatted floor			
	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2eq (kg)	CO_2 (kg)	CH_4 (g)	N_2O (g)	CO_2eq (kg)
Fitamant et al., 1999	-	-	1.10	-	-	-	1.59	-
Lägue et al., 2004	6.00	28.0	0.07	6.72	5.88	15.6	0.00	6.27
Sun et al., 2008	3.38	-	-	-	2.95	-	-	-
Guingand et al., 2010	2.48	9.7	0.19	2.78	2.31	11.2	0.24	2.66
Philippe et al., 2014	1.45	5.4	0.23	1.64	1.46	4.8	0.21	1.65

The manure can be also removed by scraping. Standard flat scraper system consists 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 per week or per day (Groensetein, 1994). With this system, reductions by 15% for CO_2 emissions and by around 50% for CH_4 and N_2O emissions can be obtained under experimental conditions (Godbout et al., 2006; Lagadec et al., 2012). However under practical conditions, this technique failed to significantly reduced CH_4 emissions (Lagadec et al., 2012).

Other systems were developed to associate manure removal and under-slat separation of liquid/solid fractions. V-shaped scraper system involves a channel with two inclined surfaces on each side of a central gutter. The liquid fraction continuously runs off by gravity towards the gutter and the solid fraction remaining on the inclined surfaces is frequently scraped (Godbout et al., 2006). When manure was scraped every 2-3 days, Godbout et al. (2006) observed unchanged CO_2 emissions but CH_4 emissions reduced by 20%, in comparison with a deep-pit emptied once a week. N_2O emissions are reduced by 50% in case of scraping frequency between 3 to 12 times a day, compared with a static pit (Lagadec et al., 2012). With the V-shaped conveyor belt system, urine constantly flows down in the middle of the belt by gravity, and feces were removed by rotating the belt (de Vries et al., 2013). This technique has shown to reduce CO_2 emissions by 47% and CH_4 emissions by 90% but increased N_2O emissions by 250%. Globally, cumulated emissions (CO_2, CH_4 and N_2O) are lowered by 80% (de Vries et al., 2013).

In addition, some original techniques were elaborated to reduce GHG emissions from pig houses. Incorporation of humic acids into slurry reduced CH_4 emissions by 34% by improving methanotrophic bacteria, but does not modified CO_2 and N_2O emissions (Shah et al., 2012). Addition of quebracho tannins into slurry reduced CH_4 emissions up to 95% thanks to noxious effect on methanogens (Whitehead et al., 2012). Soybean oil sprinkling and essential oils misting decreased CO_2 and CH_4 emissions by about 20% (Ni et al., 2008). The use of TiO2-based paints and coatings reduced CH_4 emissions up to 27% thanks to oxidative photocatalytic properties (Costa et al., 2012). Anyway, these findings have to be confirmed in further studies and, in some cases, the underlying mechanisms have to be clarified.

Releases during outside storage of slurries are influenced by numerous factors. Seasonal and weather conditions, such as air temperature, relative humidity, wind speed and rainfall, modulates the production of GHG from slurry (Lägue et al., 2004). Natural or synthetic covering were proposed to mitigate emissions by reducing emitting area, heating and turbulence at the slurry surface. However, opposite results were reported depending on the substrate and the gas (Loyon et al., 2006; Guarino et al. 2006; Van der Zaag et al., 2008). In addition, several slurry treatments have been developed to facilitate the management and to mitigate the environmental impact like solid-liquid separation, biofiltration, vermifiltration and aerobic or anaerobic treatments (Godbout et al., 2003; Lägue et al., 2004; Loyon et al., 2007; Dinuccio et al., 2008; Lessard et al., 2009; Luth et al., 2011). Among these techniques, anaerobic digestion of slurry with production of biogas rich in CO_2 and CH_4 offers interesting opportunity to significantly reduce GHG emissions thanks to lowered releases from manure, production of renewable energy (electricity and heat) and replacement of fossil fuel consumption. Adoption of anaerobic digester in a pig farm for 100 fattening places is estimate to offset a total of 125 tons CO_2eq per year (Kaparaju et al., 2011). The different techniques used to treat manure can be combined and numerous modifications/adaptations have been elaborated. The level of GHG emissions related to these techniques depends on various parameters such as the type and the duration of treatment, the stage of process, the volume and the composition of manure fraction. Thus, the specific conditions of the treatment are essential for precise environmental assessment.

3.2.2. Bedded floor systems

Compared to slatted floor systems, bedded floor systems are usually associated with reduced CH_4 emissions but increased CO_2 and N_2O emissions, with globally increased CO_2eq emissions (Table 6). The specific environment met inside the litter, especially the combination of aerobic and anaerobic area in opposition to strictly anaerobic slurry, explains these emission factors. Nevertheless, bedded systems combine a wide range of rearing techniques that impact the level of emission. Indeed, the litter may differ by the bedding material, the amount and the frequency of application, the space allowance, the litter management and the removal strategy. These parameters influence the physic-chemical characteristics of the manure, such as density, humidity, temperature, pH and C/N ratio, that interact to modulate gas emission levels (Dewes, 1996; Groenestein and Van Faassen, 1996; Misselbrook and Powell, 2005).

Table 6 –Effect of the floor type (bedded or slatted floor) on emissions (pig^{-1} day^{-1}) of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CO_2-equivalent (CO_2eq, including CO_2, CH_4 and N_2O and taken into account global warming potentials of 25 and 298 for CH_4 and N_2O, respectively)

	Bedded floor					**Slatted floor**			
	Litter type	**CO_2 (kg)**	**CH_4 (g)**	**N_2O (g)**	**CO_2eq (kg)**	**CO_2 (kg)**	**CH_4 (g)**	**N_2O (g)**	**CO_2eq (kg)**
Weaned piglets									
Cabaraux et al., 2009	Straw	0.33	0.75	0.03	0.36	0.30	0.91	0.00	0.32
Cabaraux et al., 2009	Sawdust	0.43	0.52	0.32	0.54	0.34	0.86	0.01	0.36
Fattening pigs									
Robin et al., 1999	Sawdust	-	-	4.72	-	-	-	0.79	-
Ahlgrimm and Breford, 1998	Straw	-	2.74	-	-	-	6.16	-	-
Kermarrec et al., 2002	Sawdust	-	-	5.53	-	-	-	-	-
Philippe et al., 2007a	Straw	1.97	16.03	1.11	2.70	1.74	16.32	0.54	2.31
Philippe et al., 2007b	Straw	1.77	8.88	0.68	2.19	1.61	15.20	0.67	2.19
Gestating sows									
Philippe et al., 2011a	Straw	2.83	9.20	2.27	3.74	2.41	10.12	0.47	2.80

Several bedding materials were tested regarding GHG emissions. The most frequent substrate is straw, but sawdust, wood shavings or peat can also be used (Jeppsson, 1998; Robin et al., 1999; Nicks, 2004). Compared to straw litters, sawdust litters produce less CH_4 emissions but hugely more N_2O emissions (Table 7). Globally, CO_2eq emissions are higher with sawdust mainly due to the greater contribution of N_2O emissions. Interactions within the litter may explain these results. Indeed, higher manure density observed with sawdust impairs composting process, that normally increases the manure temperature and air exchange through it (Jeppsson, 2000). Comparing different bedding types under barn conditions, Jeppsson (2000) found manure temperatures of 23.9 and 35.5°C, respectively with wood shavings and chopped straw. The lower temperatures favour activity of nitrifying and denitrifying bacteria with higher N_2O production as by-product (Sommer, 2001; Hansen et al., 2006). Contrarily, CH_4 production is very heat dependant, and lower temperature significantly diminishes the emissions (Hansen et al., 2006). By example, 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. Moreover, CH_4 production is also controlled by the rate of transport throughout the manure and oxidation (Conrad, 1989). If CH_4 production is reduced and the path of its diffusion is slow in presence of oxygen, oxidation will likely occur and consequently lower CH_4 emissions are released (Hao et al., 2011). Thus, CH_4 oxidation into CO_2 could counterbalance the reduction of CO_2 production by composting process.

The effect of the amount of substrate on GHG emissions showed conflicting results, excepted for N_2O for which reductions were systematically observed with increased amount of bedding material (Yamulki, 2006; Sommer et al., 2000; Guingand et al., 2013; Philippe al., 2013). By example, N_2O emissions were lowered by 57% when the straw supplies increased from 60 to 90 kg per fattening period (Guingand et al., 2013). Higher aeration of the litter and/or increased temperature may explain this finding. For CO_2 and CH_4 productions, the underlying mechanisms seem unclear since contradictions appear in the literature between the authors (Jeppsson, 2000; Sommer et al., 2000; Yamulki et al., 2006; Rigolot et al., 2010b; Guingand et al., 2013; Philippe et al., 2013). For instance, straw supply increased by 25% was associated with increased (+72%) CO_2 emissions according to Jeppsson (2000), while Philippe et al. (2013) observed unchanged emissions with straw rate ranging from 50 kg to 100 kg per fattening pig. Actually, interactions between the microbial pathways and the physico- chemical properties of

Table 7 – Effect of the type of substrate on emissions (pig^{-1} day^{-1}) of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CO_2-equivalent (CO_2eq, including CO_2, CH_4 and N_2O and taken into account global warming potentials of 25 and 298 for CH_4 and N_2O, respectively) associated to bedded system

	Straw-based deep litter				Sawdust-based deep litter			
	CO_2 (kg)	**CH_4 (g)**	**N_2O (g)**	**CO_2eq (kg)**	**CO_2 (kg)**	**CH_4 (g)**	**N_2O (g)**	**CO_2eq (kg)**
Weaned piglets								
Nicks et al., 2003	0.46	1.58	0.36	0.61	0.48	0.77	1.39	0.91
Cabaraux et al., 2009	0.33	0.75	0.03	0.36	0.43	0.52	0.32	0.54
Fattening pigs								
Nicks et al., 2004	1.30	7.39	0.03	1.49	1.32	4.96	2.09	2.07

the litter modulate the level of emissions with variable effects according to specific conditions. The main manure characteristics involved in these processes are dry matter content, C/N ratio, availability of carbohydrates, aeration and temperature. Regarding CH_4, extra substrate may inhibit production because of greater aeration on one hand (Rigolot et al., 2010b; Yamulki, 2006; Sommer et al., 2000), but may promote emissions by providing degradable carbohydrates for methanogenic bacteria on the other hand (Guingand et al., 2013; Philippe et al., 2013).

The effect of the frequency of straw application was addressed by Guingand et al. (2013). They observed increased emissions of CH_4 (+40%) and N_2O (+167%) when the straw was supplied every week compared to every 2 weeks while total amount of straw was similar for both frequencies. Some studies dealt with the impact of the surface of the bedded area on emissions. Based on experimental data, Hassouna et al. (2005) proposed two emission factors for N_2O emissions related to animal density: 4-12% N_{ex} with less than 2 m^2 fattening pig^{-1}, and 2-8% N_{ex} with more than 2 m^2 fattening pig^{-1}. With gestating sows, Philippe et al. (2010) measured reduction of CO_2-, CH_4- and N_2O-emissions by 12, 33 and 28%, respectively, when the available bedded area was increased from 2.5 to 3.0 m^2 per animal. Manure height also influences the level of GHG emissions. Under laboratory conditions, Dong et al. (2011) increased the manure height from 10 to 40 cm by increasing the amount of manure from 6.6 to 22.8 kg and obtained CO_2- and N_2O-emissions lowered by 53 and 11%, respectively, but doubled CH_4 emissions, resulting from more anaerobic conditions.

Like for slurry systems, manure removal strategies were proposed to reduce pollutant emissions from bedded systems. With straw-based deep litters, GHG emissions increase regularly in the course of time throughout the same fattening period, principally thanks to accumulation of dejection (Philippe et al., 2007a; Philippe et al., 2010; Philippe et al., 2012). According to Nicks et al. (2004), the rearing of three successive batches on the same litter does not increase the CO_2 and N_2O emissions from a fattening period to another but significantly increase the CH_4 emissions from 3.3 to 12.7 g CH_4 pig^{-1} day^{-1} between the first and the third batch. Thus, frequent manure removal was suggested to mitigate emissions. In this way, straw flow systems have been developed (Bruce, 1990). With this system, straw is supplied at the top of a sloped lying area and, travels down the slope with the aid of pig motion, is mixed with dung and goes out of the pen to a scrapped passage that is regularly removed. This kind of manure management is efficient to diminish the GHG emissions (Amon et al., 2007, Philippe et al., 2007b;

Philippe et al., 2012). By example, Philippe et al. (2012) measured reduction by 10, 46 and 55% for CO_2-, CH_4- and N_2O-emissions, respectively, compared to deep-litter. Globally, CO_2eq emissions (including CO_2, CH_4 and N_2O) were reduced by 50%.

During the outside storage of solid manure, air temperature seems not to significantly influence the level of emissions, contrary to wind speed or rainfall episode (Wolter et al., 2004). Manure operation like turning, stacking or covering impact on GHG emissions but with some controversial findings between studies (Hellman et al., 1997; Paillat et al;, 2005; Szanto et al., 2007; Jiang et al., 2013). Interlinked relationships between biological, physical and chemical factors inside the manure heap explain these discrepancies.

3.3. Nutrition

The main dietary strategies proposed for abatement of pollutant gas emissions are manipulation of the contents in crude protein and fibres. Some dietary additives were also studied for their impact on GHG emissions.

3.3.1. Crude protein content

Diets reduced in crude protein content (CPC) but supplemented with amino acids were given to pigs to match the protein supply with their growth potential and so to improve the efficiency of protein utilization, with similar zootechnical performance but reduced N excretion and NH_3 production as consequences (Philippe et al., 2011b). Thus, it was suggested that lower CPC could also reduce N_2O emissions since NH_3 is precursor of its formation (Misselbrook et al., 1998). However, experiments failed to corroborate this hypothesis (Table 8). Indeed, laboratory-scale experiments based on slurry samples resulted in similar N_2O emissions despite CPC reduced by 15-20% (Clark et al., 2005; Le et al., 2009; Osada et al., 2011). Under barn conditions with fattening pigs on litter, Philippe et al. (2006) reported doubled N_2O emissions with CPC reduced by 18%. It was also assumed that lower CPC could reduce CO_2- and CH_4-emissions thanks to improved nutrient utilization, but contradictory findings were noticed for these gases (Table 8). In respiratory chambers, most of the studies showed non-significant difference in CO_2-exhalation despite CPC reduction up to 45% (Atakora et al., 2003, 2005, 2011a and 2011b). Quiniou et al. (1995) measured respiratory CO_2 production increased by 7% with fattening pigs while Atakora et al. (2002) noted decreased production by 5 to 7% with reproductive sows. Regarding CH_4 emissions, authors reported reductions ranging

Table 8 – Effects of reduction in diet crude protein content (CPC) on emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CO_2-equivalents (CO_2eq, including CO_2, CH_4 and N_2O and taken into account global warming potentials of 25 and 298 for CH_4 and N_2O, respectively)

References	CO_2	CH_4	N_2O	CO_2eq	Context
Quiniou et al., 1995	+7%	-	-	-	Respiratory chambers, Fattening pigs, 17.7 vs. 24.3% CPC
Atakora et al., 2002	-5%	-	-	-	Respiratory chambers, Gestating sows, 14.8 vs. 19.3% CPC
Atakora et al., 2002	-7%	-	-	-	Respiratory chambers, Lactating sows, 12.0 vs. 16.3% CPC
Atakora et al., 2003	NS	-60%	-	-	Respiratory chambers, Non-pregnant sows, 11.% vs. 14.6% CPC
Atakora et al., 2005	NS	NS	-	-	Respiratory chambers, Fattening pigs, 11.2 vs. 16.8% CPC
Atakora et al., 2011a	NS	-27%	-	-	Respiratory chambers, Fattening pigs, 12.0 vs. 19.5% CPC
Atakora et al., 2011b	NS	-19%	-	-	Respiratory chambers, Fattening pigs, 16.2 vs. 19.0% CPC
Clark et al., 2005	+10%	+10%	NS	+10%	Slurry samples, Fattening pigs, 13.9 vs. 16.8% CPC
Velthof et al., 2005	-	-21%	-	-	Slurry samples, Fattening pigs, 14.2 vs. 18.0% CPC
Le et al., 2009	NS	NS	NS	NS	Slurry samples, Fattening pigs, 12.0 vs. 15.0% CPC
Osada et al., 2011	-	NS	NS	-	Slurry samples, Fattening pigs, 14.5 vs. 17.0% CPC
Philippe et al., 2006	NS	-13%	+96%	+7%	Pens with fattening pigs pigs on straw litter, 14.4 vs. 17.6% CPC

from 13% under field conditions (Philippe et al., 2006) to 60% in respiratory chambers (Atakora et al., 2002). This effect could be explained by the greater VFA content in the manures produced from the diet protein as seen VFA can be transformed into CH_4 (Velthof et al., 2005). Contrarily, non-significant differences or increases of CH_4 production were also obtained by some authors in case of reduced CPC (Atakora et al., 2005; Clark et al., 2005; Le et al., 2009; Osada et al., 2011). Cumulated GHG emissions (including CO_2, CH_4 and N_2O) reported by Philippe et al. (2006) with pigs on litter were increased by 7% with diet reduced in CP due to higher contribution of N_2O despite lower CH_4 emissions.

3.3.2. Dietary fibre

Several studies dealt with the impact of dietary fibres on GHG emissions (Table 9). It is established that diets rich in fibres increase CH_4 production from both source, the animal and the manure. The effect of dietary fibres on enteric CH_4 production is addressed in the section 2.2.1. Higher CH_4 releases from slurry in case of fibrous diets were reported by some authors under laboratory conditions (Clark et al., 2005; Velthof et al. 2005; Jarret et al., 2012). By example, Jarret et al. (2012) compared CH_4 production from slurries of fattening pigs fed a conventional diet (11% NDF) or a fibrous diet with 20% of dried distiller's grain with soluble (DDGS; 14% NDF) and obtained higher emission (+76%) with the fibrous diet. They explained this result by the lower digestibility of high fibre diets and thus the higher quantity of excreted OM (0.32 vs. 0.19 kg pig^{-1} day^{-1}) whereas B_0 of excreta did not differ significantly between treatments (around 0.38 m^3 per kg OM). Contrarily to these results, Clark et al. (2005) did not observed significant difference in CH_4 emissions under *in vitro* conditions whatever the fibre content. At house level, CH_4 emissions are increased by 13 to 52% with fibrous diets as well with slatted floor as bedded floor (Philippe et al., 2009; Pepple et al., 2011; Philippe et al., 2012 and 2013).

Regarding CO_2 production, conflicting results were reported depending of the study and the source of emissions (Table 9). By example, Schrama et al. (1998) measured CO_2 exhalation lowered by 25% as a consequence of a reduction of the pig activity. At house level, Philippe et al. (2009) observed emissions increased by 24% with a diet based on sugar beet pulp (48% NSP) compared to a conventional diet based on cereals (26% NSP). The reduced feed efficiency observed with fibrous diet could explain the result.

Table 9 – Effects of dietary fibre content on emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and CO_2-equivalents (CO_2eq, including CO_2, CH_4 and N_2O and taken into account global warming potentials of 25 and 298 for CH_4 and N_2O, respectively)

References	CO_2	CH_4	N_2O	CO_2eq	Context
Schrama et al., 1998	-25%	+96%	-	-	Respiratory chambers, fattening pigs, 12 vs. 18% NSP (0 vs. 17% SBP)
Wang et al., 2004	+6%	+153%	-	-	Respiration chambers, Fattening pigs, 4 vs. 11.6 % NSP (0 vs. 12% SBP)
Li et al. 2011	-7%	+93%	-	-	Environmentally controlled pens, fattening pigs, 32 vs. 40% NDF (0 vs. 20% DDGS)
Clark et al., 2005	-17%	NS	NS	-5%	Slurry samples from fattening pigs, 0 vs. 20% SBP
Velthof et al., 2005	-	+74%	-		Slurry samples from fattening pigs, 13 vs. 25% NSP
Jarret et al., 2012	-	+76%	-		Slurry samples from fattening pigs, 11 vs. 14% NDF (0 vs. 13% DDGS)
Philippe et al., 2009	+24%	+13%	-61%	+5%	Pens with gestating sows on straw litter, 26 vs. 48% NSP (7 vs. 42% SBP)
Pepple et al., 2011	-13%	+45%	NS	+28%	Buildings with fattening pigs on slatted floor, 0 vs. 20% DDGS
Philippe et al., 2013	-9%	+33%	NS	-6%	Pen with fattening pigs on slatted floor, 18 vs. 30% NSP (0 vs. 23% SBP)
Philippe et al., 2012b	NS	+44%	NS	+6%	Pen with gestating sows on slatted floor, 25 vs. 44% NSP (0 vs. 37% SBP)
Philippe et al., 2012b	+14%	+52%	-40%	+9%	Pen with gestating sows on straw litter, 25 vs. 44% NSP (0 vs. 37% SBP)

NSP: Non-starch polysaccharides; SBP: Sugar beet pulp; NDF: neutral detergent fibre; DDGS: dried distiller's grain with soluble.

N_2O emissions from slurry-based systems are unaffected by the dietary fibre content (Clark et al., 2005; Pepple et al., 2011; Philippe et al., 2012a and 2012b), in contrary to bedded systems, for which emissions are reduced with high-fibre diets (Philippe et al., 2009 and 2012b). Actually with fibrous diet, the pig motivation to manipulate and to chew the straw is reduced, as a sign of greater satiety (Philippe et al., 2008). Thus, the litter is more aerated with longer wisps of straw, which limit N_2O production.
Globally, cumulated GHG emissions (combining CO_2, CH_4 and N_2O) seems few influenced by the dietary fibres as seen authors reported emissions at house level ranging from -6 to +9% compared to conventional diet (Philippe et al., 2009; 2012a and 2012b), excepted for Pepple et al. (2011) who noticed CO_2eq emissions increased by 28%. They explained this result by the large contribution of CH_4 in their experimental conditions due to long storage duration of slurries inside the building.

3.3.3. Feed additives

Several feed additives were studied for their influence on environmental factors, especially on ammonia emissions, but few experiments dealt with greenhouse gas emissions.
Most of the studies argued that feed supplementations that improve nutrients digestibility and growth performance potentially reduce pollutant gases emissions on an absolute scale and per product unit (Moehn et al., 2011). However, this statement was rarely experimentally tested and validated.
Cellulases and hemicellulases were added to diets to counterbalance the anti-nutritional effects of fermentable fibres and to improve animal performance (O'Shea et al., 2010). A further beneficial effect may be a reduction in CH_4 production by enteric bacteria, which are linearly related to fibres ingestion. However, Moehn et al. (2011) observed a tendency for increased CH_4 emission despite xylanase supplementation.
Dietary inclusion of acidifying salts was also suggested to modify GHG production. Yet, Aarnink et al. (2008) did no observe significant difference in CH_4 and N_2O emissions despite the addition of 1% of benzoic acid in the diet of fattening pigs. With diet supplemented with 2% of benzoic acid, Eriksen et al. (2010) measured a transient reduction in CH_4-emission from slurries stored under laboratory conditions (from day 20 to 34 of storage). They explained the result by the inhibition of methanogenic bacteria possibly due to reduction in manure pH, toxic effect of sulphides or direct

impact of benzoic acid. The temporality of the reduction could reflect the adaptation of the bacteria to slurry acidification.

Yucca extract inclusion was proposed to inhibit urease activity and chemically convert or bind NH_3 (Duffy and Brooks, 1998) with improvement of performance and health status of pigs (Colina et al., 2001). However, Amon et al. (1995) measured increased CO_2 production with dietary addition of *Yucca shidigera* extract. The effects on CH_4 and N_2O emissions are still unknown.

Phytase addition, primarily used to reduce phosphorus excretion, has been shown to increase feed efficiency and protein deposition and could possibly lead to a decrease in emissions (Ball et al., 2003). But to the best of knowledge, phytase addition has not been studied for its effect on GHG emissions.

Zeolites incorporation resulted in improved digestibility and performance (Papaioannou et al., 2002; Kim et al., 2005; Leung et al., 2007) and reduced manure nutrient content (Kim et al., 2005; Milic et al., 2006; Tiwari et al., 2009). Nevertheless, potential effects on GHG emissions were not experimentally confirmed.

Probiotics agents are believed to improve microbial environment in the gut, with better digestibility, performance and health status as consequences (Fuller, 1989; Tsukahara et al., 2001). Under laboratory conditions, Tsukahara et al. (2001) measured emissions from intestinal content of piglets fed diet supplemented with a mixture of live lactic acid bacteria (*Lactobacillus acidophilus*, *Bifidobacterium bifidum* and *Enterococcus faecalis*). They obtained reductions by about 50 and 35% for CO_2-and CH_4-emissions, respectively, explained by the fact that lactic acid bacteria are stoichiometrically less favourable to gas production (Stanier et al., 1986). Barn experiments would be carried out to confirm these findings on a larger scale.

4. Emissions at pig house level

Several authors measured GHG emissions from pig houses under practical conditions. Table 10 summarizes results from studies involving CO_2, CH_4 and N_2O together for different animal types kept on slatted floors.

Table 10 - Emissions factors at house level for carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) related to the physiological stage of the pigs (kept on slatted floor).

Physiological stage	Country	Greenhouse gases emissions (kg CO_2eq $LU^{-1}.day^{-1}$)			
		CO_2	CH_4	N_2O	Total
Gestating sows					
Lägue et al., 2004	Canada	11.98	2.13	0.00	14.10
Dong et al., 2007	China	5.92	0.24	0.22	6.38
Zhang et al., 2007	USA	8.16	2.39	0.00	10.55
Costa and Guarino, 2009	Italy	8.85	3.30	0.81	12.96
Philippe et al., 2011a	Belgium	5.70	0.60	0.33	6.63
Stinn et al., 2011	USA	8.95	7.07	0.03	16.04
Mean		8.26	2.62	0.23	11.11
Farrowing sows					
Lägue et al., 2004	Canada	21.50	4.56	0.00	26.06
Dong et al., 2007	China	7.49	0.24	0.16	7.89
Zhang et al., 2007	USA	14.08	6.69	0.00	20.77
Stinn et al., 2011	USA	27.86	3.59	0.07	31.53
Mean		17.73	3.77	0.06	21.56
Weaned piglets					
Lägue et al., 2004	Canada	29.85	14.69	0.00	44.54
Dong et al., 2007	China	29.67	1.46	0.38	31.51
Cabaraux et al., 2009	Belgium	10.70	0.74	0.05	11.48
Costa and Guarino, 2009	Italy	6.00	0.61	1.08	7.69
Mean		19.05	4.37	0.38	23.81
Fattening pigs					
Nicks et al., 2005	Belgium	13.86	3.24	0.75	17.85
Dong et al., 2007	China	16.73	0.80	0.26	17.79
Philippe et al., 2007a	Belgium	12.84	3.01	1.19	17.04
Costa and Guarino, 2009	Italy	13.64	4.75	0.97	19.35
Palkovicova et al., 2009	Slovak Republic	14.36	5.76	0.91	21.02
Guingand et al., 2010	France	17.82	1.95	0.47	20.24
Li et al., 2011	USA	16.20	0.53	1.71	18.44
Ngwabie et al., 2011	Sweden	16.38	3.78	0.37	20.53
Mean		15.23	2.98	0.83	19.03

CO_2eq : Emissions of CO_2-equivalents, including CO_2, CH_4 and N_2O, taken into account global warming potentials of 25 and 298 for CH_4 and N_2O, respectively.
LU: livestock unit, equals to 500 kg BW. In case of lack of data, default values for body weight (BW) were estimated to 200, 220, 18 and 70 kg for gestating sows, farrowing sows (including piglets), weaned piglets and fattening pigs, respectively.

CO_2 emissions related to fattening pigs are quite identical between studies while corresponding values for the other animal type show greater variation, especially for weaned piglets. Similar findings were also observed by Philippe et al. (2011b) about NH_3 emissions. The discrepancy between studies may be attributed to differences in housing conditions, ventilation system, management practices, diet formulation and gas measurement method. Nevertheless, the average emission factors proposed by physiological stage seem consistent between each other. Indeed, gestating sows present the lowest value (8.26 kg CO_2 LU^{-1} day^{-1}, or 3.3 kg CO_2 sow^{-1} day^{-1}), as influenced by their low feed intake (restricted feeding, low energy density of the diet) and metabolism. Farrowing sows (including piglets) and weaned piglets are associated with the highest emissions (17.73 kg CO_2 LU^{-1} day^{-1}, or 8.87 kg CO_2 sow^{-1} day^{-1}, and 19.05 kg CO_2 LU^{-1} day^{-1}, or 0.69 kg CO_2 pig^{-1} day^{-1}, respectively), as consequence of ad libitum feeding and intensive productive status (milk production and growth). Emissions related to fattening pigs (15.3 kg CO_2 LU^{-1} day^{-1}, or 2.1 kg CO_2 pig^{-1} day^{-1}) are slightly lower than the latter.

CH_4 emissions reported in the literature present a large range of variation within each animal type. In addition to the variation factors exposed above for CO_2, the manure removal strategy and the storage duration inside the building seems to play an important role regarding the level of emission. By example with gestating sows, Stinn et al. (2011) measured CH_4 emissions of 7.07 kg CO_2eq LU^{-1} day^{-1} with semi-annually slurry removing while Dong et al. (2007) measured CH_4 emissions of 0.24 kg CO_2eq LU^{-1} day^{-1} with manure gutter and continuous discharge of urine out of the barn associated with removal of solid manure twice a day. For the other animal types, higher emissions were also observed with longer inside manure storage duration. On average, the mean emission factors expressed per LU does not differ importantly between the physiological stage, ranging from 2.62 kg CO_2eq LU^{-1} day^{-1} for gestating sows, to 4.37 kg CO_2eq LU^{-1} day^{-1} for weaned piglets, with intermediate values for fattening pigs (2.98 kg CO_2eq LU^{-1} day^{-1}) and farrowing sows (3.77 kg CO_2eq LU^{-1} day^{-1}). Corresponding values expressed par animal are 41.9, 6.3, 16.7 and 78.5 g CH_4 day^{-1}), respectively. The CH_4 emissions associated with gestating sows could be considered quite low as seen the high fibre content of their diet and their large fermentative capacity. Actually, these effects are counterbalanced by the restricted feeding usually applied for this stage.

N_2O emissions measured from pig houses fitted with slatted floor were relatively low whatever the animal type. In some experiments (Lägue et al., 2004; Zhang et al., 2007), the production was even lower than the detection limit of the measurement equipment, with small mean values as consequence. In this context, important relative differences between studies or physiological stages do not have relevant meaning. Thus, it seems more appropriate to consider a generic emission factor for all the stages. Based on values reported in table 10, an average emission of 0.40 kg CO_2eq LU^{-1} day^{-1} could be proposed.

Total GHG emissions from buildings are estimated to 11.11 kg CO_2eq $LU^{-1}day^{-1}$ for gestating sows and around 20 kg CO_2eq $LU^{-1}day^{-1}$ for lactating sows, weaned piglets and fattening pigs, reflecting the relative metabolism rate of each animal type.

The contribution of each physiological stage on GHG emissions intensity expressed per unit of product are presented in table 11. Globally, GHG emissions from pig houses are estimated to 448.4 kg CO_2eq per slaughter pig produced or 4.87 kg CO_2eq per kg carcass. Fattening period accounts for more than 70% of total emissions while gestation, lactation and weaning periods contribute each to about 10% of total emissions. Emissions of CO_2, CH_4 and N_2O contribute to 81, 17 and 2% of total emissions from buildings, representing 3.87, 0.83 and 0.17 kg CO_2eq per kg carcass, respectively. Several authors elaborated live cycle assessment (LCA) studies to estimate emissions intensity of pig production. Reported values ranged from 3.07 to 5.79 kg CO_2eq per kg carcass (Vergé et al., 2009; Pelletier et al., 2010; Lesschen et al., 2011; Weis and Leip, 2012). These models excluded CO_2 emissions from respiration and manure but included GHG emissions for feed production, manure storage and spreading, and energy consumption. Discrepancy between studies comes from difference in methodology, type of pig production, boundary of the system, emissions categories and allocation. With regards to the values calculated in this paper, it can be assumed that 1) CO_2 emissions from pig houses (animal respiration and releases from manure) are in the same range of values reported in LCA studies, 2) cumulated CH_4- and N_2O-emissions from pig houses account for 15 to 30% of total emissions estimated with LCA methodology.

Table 11 –Contribution of the physiological stage on greenhouse gases emissions per unit of product (assuming no allocation to slaughter by-products)

Physiological stage	Days	Greenhouse gases emissions (kg CO_2eq^a)		
		day^{-1} animal^{-1b}	slaughter pig^{-1c}	kg carcass^{-1d}
Dry and gestating sows	125	4.44	55.6	0.60 (12%)
Lactating sows[e]	28	10.78	30.2	0.33 (7%)
Weaned piglets[f]	50	0.86	42.8	0.47 (10%)
Fattening pigs[g]	120	2.67	319.9	3.48 (71%)
Total	323	-	448.4	4.87 (100%)

[a]: CO_2eq: CO_2-equivalent, including CO_2, CH_4 and N_2O and taken into account global warming potentials of 25 and 298 for CH_4 and N_2O, respectively
[b]: For CO_2 and CH_4, derived from data presented on table 10; for N_2O, generic emission factor of 0.40 kg CO_2eq per livestock unit (equal to 500 kg BW).
[c]: Based on 10 slaughtered pigs per litter
[d]: Based on carcass weight of 92 kg (liveweight of 118 kg and dressing percentage of 78%)
[e]: Including piglets until 8 kg BW
[f]: From 8 to 28 kg BW with 400 g of average daily gain
[g]: From 28 to 118 kg BW with 750 g of average daily gain

5. Conclusion

This paper focuses on techniques that can be used to reduce CO_2-, CH_4- and N_2O-emission by animals and manures from pig buildings. A large range of factors influencing the level of GHG production from pig houses were pointed out in the literature but few of them can be considered indubitably as mitigation techniques because some strategies show contradictory effects depending on the gas, the circumstances and the study. By example, implementation of partly slatted floor instead of fully slatted floor seems efficient to reduce CO2 emissions but conflicting findings were reported regarding CH_4- and N_2O-emissions. With bedded systems, the use of sawdust as substrate reduces the CH_4 emissions but increases the N_2O emissions compared with straw based litter. Anyway, solid manures produce significantly more N_2O than slurry, which constitutes the main inconvenient of bedded systems. Actually, the large number of gas synthesis pathways and source of emissions makes the cumulated GHG emissions difficult to predict. Moreover, microbial, physical, chemical, physiological and behavioural parameters interact together and modulate the level of emissions function of particular conditions. By example, litter-based systems have indirect impact on emissions due to influences on pig activity, which can modify CO_2 exhalation, exploratory behaviour, which can alter litter characteristics and releases from manure, and substrate ingestion, which can increase enteric CH_4 emissions. Therefore, further investigations are still needed to identify and to control these influencing parameters and their interactions under specific circumstances.

Nevertheless among the numerous influencing factors, frequent manure removal seems efficient to reduce concurrently CO_2-, CH_4- and N_2O-emissions from buildings for both slurry- and litter-based systems. Total emissions, including storage, will be reduced provided lower outside temperature than inside or specific treatment. Indeed, manure removal operations can be associated with other techniques like liquid/solid fractions separation or manure anaerobic treatments. These complementary treatments give also opportunities to facilitate manure handling and recycling and to further reduce emissions. Given the multiplicity of techniques, adaptations and combinations, the implementation and the environmental assessment of processes should be evaluated in regard to the context.

Several feeding strategies were also investigated assuming improved nutrient utilization could lower GHG emissions. However, this statement was not systematically observed in experiments. Diets supplemented with feed additives like acidifying salts, yucca extracts or probiotics are not effective to significantly reduce the emissions. Even for CH_4 emissions that are positively related to fibres intakes, inclusion of cellulase and hemicellulase fails to diminish durably the production. Similarly, reduction of diet CPC that is well-known to reduce N excretion, fails to limit N_2O releases from manures. However, other nutritional options could be also examined in the future and appear effective in reducing emissions. Feeding strategies offer the advantage of being easy to implement and rapid to adapt function of availability and cost of raw materials that fluctuate temporally.

Good management practices that respect the physiological requirement of the animals and that promote their zootechnical potential will have beneficial consequences on performance and indirectly on GHG emissions intensity. In light of this, factors like design of the building, regulation of bioclimatic parameters, sanitary status of the herd and genetic selection can modulate the level of GHG production.

The choice for a rearing technique is also guided by other elements, such as animal welfare, agronomical values of manure, investment and operating costs. Specific field conditions lead to decision in favour of mitigation techniques. Options presented in this review may contribute to reduce emission intensity of pig production, but to be globally efficient, they have to be integrated on a larger scale taken into account supplementary emissions associated to pre-, on- and post-farm processing like feed production, energy consumption, manure spreading and transportation of animal and products.

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Phase expérimentale

1. EMISSIONS D'AMMONIAC ET DE GAZ A EFFET DE SERRE ASSOCIEES A L'ENGRAISSEMENT DE PORCS CHARCUTIERS SUR CAILLEBOTIS OU SUR LITIERE DE PAILLE ACCUMULEE

En production porcine, les porcs sont généralement hébergés sur sol à caillebotis avec récolte des déjections sous forme de lisiers. Depuis les années 80, l'élevage sur litière avec récolte des effluents sous forme de fumiers a connu un regain d'intérêt car il est assimilé à un meilleur bien-être animal (Tuyttens, 2005) et une réduction des nuisances olfactives (Kaufmann, 1997). En améliorant ainsi l'image de marque des productions porcines, cette technique rejoint les attentes des consommateurs et facilite l'acceptation par le voisinage de l'implantation de nouvelles porcheries (Chevrant-Breton et Daridan, 2003). Actuellement, les enjeux environnementaux prennent une importance grandissante. Il est alors essentiel d'évaluer ce type d'hébergement quant à ses effets sur le milieu. Si les émissions de gaz polluants (NH_3, N_2O, CH_4 et CO_2) associées au système à caillebotis ont déjà fait l'objet de nombreuses recherches (par exemple Groot Koerkamp et al.,, 1998, et Aarnink et al. 1995), les travaux portant sur les litières sont plus rares. De plus, peu d'études comparent les deux techniques dans des conditions standardisées. Dès lors, l'objectif de cette étude était de comparer les émissions de NH_3, N_2O, CH_4 et CO_2 lors de l'engraissement de porcs charcutiers sur sol à caillebotis total ou sur litière de paille accumulée.

Pour réaliser cette étude, deux locaux expérimentaux, similaires en volume (103 m^3) et en surface (30 m^2), ont chacun été équipés d'une loge pouvant héberger des groupes de 16 porcs, l'un d'une surface de 12,2 m^2 (0,76 m^2 $porc^{-1}$) avec sol à caillebotis total en béton (15,6% de vide), et l'autre d'une surface de 19,2 m^2 (1,20 m^2 $porc^{-1}$) avec sol paillé. En début d'engraissement, 500 L d'eau ont été déversés dans la fosse à lisier de la loge à caillebotis afin d'éviter la formation précoce d'une croûte et de faciliter l'évacuation des lisiers en fin d'engraissement et 375 kg de paille de blé entière ont été disposés dans la loge paillée afin de constituer la couche initiale de litière d'une épaisseur d'environ 30 cm. En cours d'engraissement, de la paille était apportée régulièrement en fonction de l'état de propreté des animaux et de la loge pour atteindre une quantité totale de 750 kg de paille en fin d'engraissement (47 kg $porc^{-1}$). Cinq bandes successives de 32 porcs charcutiers (Piétrain x Landrace belge), répartis uniformément en deux groupes en fonction du poids et du sexe, ont été hébergés dans ces locaux.. D'un poids initial avoisinant les 24 kg, les porcs ont été engraissés durant environ 4 mois jusqu'à un poids final proche de 110 kg. A la fin de chaque période d'engraissement, les effluents (lisiers et fumiers) étaient évacués et les loges étaient nettoyées. La ventilation des locaux se faisait au moyen de ventilateurs extracteurs (1 par loge) et de manière contrôlée avec adaptation automatique du débit de ventilation en fonction de la température, ces deux paramètres étant mesurés et enregistrés en continu (Fancom, Panningen, Pays-Bas). Les concentrations en gaz ont été mesurées dans les locaux expérimentaux et dans le couloir d'apport d'air par détection photo-acoustique infrarouge au moyen d'un moniteur équipé pour la mesure simultanée de NH_3, N_2O, CH_4, CO_2 et H_2O (1312 Photoacoustic Multi-Gas Monitor, Innova Air Tech Instruments, Nærum, Denmark). Quatre séries de mesures de six jours consécutifs réparties de manière homogène sur la période d'engraissement ont été réalisées pour chaque bande de porcs. Les émissions (E_{gaz}) ont été calculées sur base horaire grâce à l'équation suivante :

$E_{gaz} = D \times (C_i - C_e)$,

avec D, le débit de ventilation (kg air h^{-1}), et C_i et C_e, respectivement la concentration en gaz dans l'air du local expérimental et du couloir d'apport d'air (mg kg^{-1} air). Les résultats d'émissions ont été testés au moyen d'un modèle mixte pour données répétées (SAS, Mixed Proc) en incluant l'effet du type de sol (1 dl), de la série de mesure (3 dl) et de l'interaction sol-série (3 dl) avec 144 données (24 heures x 6 jours) par série de mesure.

Les émissions de NH_3 ont été plus que doublée avec le sol paillé en comparaison au sol latté (13,1 *versus* 6,22 g NH_3 $porc^{-1}$ $jour^{-1}$, $P<0,001$). Ce résultat confirme des études précédentes qui avaient montré des émissions augmentées de +30% à +70% avec des litières accumulées de paille (Nicholson et al., 2000 ; Balsdon et al., 2001). La plus grande surface d'émission combinée à des températures et un pH plus élevés des litières peut expliquer ces émissions plus importantes (Andersson, 1996).

Les émissions de N_2O ont également été plus que doublées lors de l'élevage sur litière (1,11 *versus* 0,54 g N_2O $porc^{-1}$ $jour^{-1}$, $P<0,001$). La combinaison au sein des litières de zones aérobies proches de zones anaérobies favorise la production de N_2O en tant que sous–produit des réactions de nitrification-dénitrification qui en cas de conditions suboptimales n'aboutissent pas complètement à la synthèse de N_2, gaz non-polluant.

Les émissions de CH_4 associées aux deux types de logement étaient comparables avec environ 16 g CH_4 porc^{-1} jour^{-1} ($P>0,05$). Le méthane provient de la dégradation strictement anaérobie de la matière organique. En porcherie, la méthanogénèse a lieu dans l'intestin des animaux et dans l'effluent (Hellmann et al., 1997). La production entérique est proportionnelle à l'ingestion de fibres et à la capacité fermentaire des animaux. Elle est également influencée par l'origine botanique des fibres, leur structure, leur solubilité et leur fermentescibilité (Philippe et al., 2008). Pour des porcs charcutiers recevant une alimentation standard, la production de CH_4 entérique est de l'ordre de 2,4 à 4,1 g par jour (IPCC, 2006 ; Vermorel et al., 2008 ; Dämmgen etal., 2012). Dans les effluents, la méthanogenèse est principalement réalisée par une flore mésophile (25°-40°C) en condition anaérobie et à un pH proche de la neutralité (Hellmann et al., 1997). Lors de l'élevage sur litière, les émissions entériques peuvent être favorisées par l'ingestion de paille, et les émissions à partir des litières par l'apport de matière organique que constitue la paille et la chaleur générée au sein des fumiers. A l'inverse, les émissions peuvent être réduites par le caractère plus aéré des fumiers en comparaison aux lisiers (Amon et al., 2006 ; Yamulki, 2006). Dans notre étude, ses différents facteurs de variation semblent s'être neutralisés pour aboutir à des émissions identiques avec les deux types de sol.
Les émissions de CO_2 ont été plus élevées avec l'élevage sur litière (1,97 *versus* 1,74 kg CO_2 porc^{-1} jour^{-1}, $P<0,001$). La source principale de CO_2 est la respiration des animaux qui représente environ 1,6 kg par jour pour un porc de 65 kg (Ni et al., 1999a; CIGR, 2002). Dans l'effluent, le CO_2 a pour origine l'hydrolyse de l'urée et les fermentations anaérobie et aérobie de la matière organique. Dans les fumiers, ce dernier processus, aussi appelé compostage, semble particulièrement favorisé (Hellmann et al., 1997; Wolter et al., 2004), ce qui expliquerait les niveaux d'émission plus élevés.

En conclusion, dans les conditions expérimentales de cette étude, le système d'hébergement sur litière de paille accumulée pour porcs charcutiers est associé à des émissions plus élevées de NH_3, N_2O et CO_2 en comparaison au système sur caillebotis total alors que le niveau d'émission du CH_4 semble moins impacté par le type de logement. Les émissions cumulées de GES (incluant N_2O, CH_4 et CO_2) sont globalement plus élevées avec l'hébergement sur paille en raison de la contribution plus importante du N_2O et du CO_2.

Comparison of ammonia and greenhouse gas emissions during the fattening of pigs kept either on fully slatted floor or on deep litter

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Pig - Slatted floor – Litter – Ammonia - Greenhouse gases - Water vapour

Abstract

Five successive batches of fattening pigs were raised, each during a four month period, on a totally concrete slatted floor in one experimental room and on straw-based deep litter in another. The rooms were automatically ventilated to maintain a constant ambient temperature. Available floor space was of 0.75 m^2 per pig kept on the slatted floor and 1.20 m^2 per pig kept on the deep litter. With this last system, about 46 kg of straw were supplied per pig throughout a fattening period. The slurry pit was emptied and the litter removed after each batch. Once a month, the emissions of ammonia (NH_3), nitrous oxide (N_2O), methane (CH_4), carbon dioxide (CO_2), and water vapour (H_2O) were measured continuously for 6 consecutive days by infra-red photoacoustic detection. The performance of the animals was not significantly different according to the floor type. Gaseous emissions from pigs raised on the slatted floor and on the deep litter were, respectively, 6.2 and 13.1 g per pig per day for NH_3, 0.54 and 1.11 g per pig per day for N_2O, 16.3 and 16.0 g per pig per day for CH_4, 1.74 and 1.97 kg per pig per day for CO_2 and 2.48 and 3.70 kg per pig per day for H_2O. Except for the CH_4 emissions, all the differences were significant ($P<0.001$). Thus, pig fattening on deep litter releases nearly 20% more greenhouse gases than on slatted floor, with 2.64 and 2.24 kg of CO_2-equivalents, respectively ($P<0.001$). Whatever the floor type, emissions increased from the beginning to the end of the fattening periods by about 5 times for NH_3, 4 times for N_2O, 3 times for CH_4 and 2 times for CO_2 and H_2O. Correlation coefficients between CO_2-

emissions and H_2O, NH_3 and CH_4 emissions were, on average for both floor types, 0.82, 0.77 and 0.74, respectively. Although rearing pigs on straw generally has a good brand image for the consumer, this rearing system produces more pollutant gases than keeping pigs on slatted floors.

1. Introduction

Since the 1950s and the development of intensive livestock production, in Western Europe, the straw based litter system in pig production has been progressively replaced by the slatted floor system. However, since the 1980s, there has been a renewed interest in the litter system because this method is associated with improved pig welfare (Tuyttens, 2005) and reduced odour nuisance (Bonazzi and Navarotto, 1992; Shilton, 1994; Kaufmann, 1997). Thus, this system fits in with consumer expectations about the brand image of livestock and makes easier the acceptance by the neighbourhood of new piggery establishments (Pigeon and Drolet, 1996; Chevrant-Breton and Daridan, 2003). However, the real impact of the litter system on the environment has to be assessed, particularly its contribution to pollutant gas emissions such as ammonia and greenhouse gases. Authors have already discussed some aspects of this issue (Andersson, 1996; Groot Koerkamp et al., 1998; Jeppsson, 2000; Møller et al., 2000; Nicholson et al., 2000; Sommer and Møller, 2000; Nicks, 2004; Nicks et al., 2004; Hassouna et al., 2005) but few evaluated several gases under field conditions.

Ammonia (NH_3) emissions contribute to soil and water acidification (Degré et al., 2001; United Nations, 2001). In addition, ammonia is well known as a toxic gas that irritates the respiratory tract (Portejoie et al., 2002) at concentrations exceeding 15 p.p.m. Greenhouse gas emissions associated with livestock production are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Pain, 1998; Degré et al., 2001; Nicks, 2004). However, agriculture is also a CO_2-consumer through plant photosynthesis. CO_2 contribution to the greenhouse effect is less important than that of CH_4 and N_2O, whose warming potentials are, respectively, 23 and 296 times that of CO_2 (Intergovernmental Panel on Climate Change, 2001). N_2O also contributes to the destruction of the ozone shield. Nowadays, national and international legislation tends to impose a reduction of the emissions of these gases. For example, according to the Gothenburg Protocol signed by environmental ministers from Europe and North America in 1999, ammonia emissions will be cut by almost 20% by 2010 in comparison with the 1990 level. Consequently, it is important to evaluate the emissions from different production sectors. In France, it is estimated that 80% of NH_3 emissions come from agriculture as do 76% of N_2O emissions, 70% of CH_4 emissions and 14% of CO_2 emissions (CITEPA, 2005). In order to plan a reduction, it is important to know precisely the emissions associated with different production techniques.

In pig production, although gas emissions from the slatted floor system are rather well documented, there is a lack of data concerning litter systems and the comparison between the two systems (European Commission, 2003). So, the aim of this study was to compare in standardized conditions ammonia, nitrous oxide, methane and carbon dioxide emissions from pig houses with fattening pigs kept either on slatted floor or on straw based deep litter. Water vapour emissions from the two systems were also measured, as these emissions are a key factor in calculating the ventilation needs of animal buildings (CIGR, 2002).

2. Materials and methods

2.1. Experimental housing

Two experimental rooms, similar in volume (103 m^3) and surface (30 m^2), were arranged, one with a concrete totally slatted floor pen (void percentage of 15.6%) and another with a straw based deep litter pen (Figure 1). Groups of 16 pigs were housed in both pens. The floor space of the pens was 12.2 m^2 and 19.3 m^2 for the slatted and the bedded systems, respectively. Five successive batches of pigs were fattened during the experiment. Each batch was in the experimental rooms for four months. Before each fattening period, about 500 l water was poured into the slurry pit in order to have a layer of about 4 cm to limit initial odour and gas production, and 375 kg of whole wheat straw was used to constitute the initial deep litter of about 30 cm depth. Throughout the fattening period, fresh straw was supplied regularly up to a total amount of 750 kg. At the end of each fattening period, the slurry pit was emptied and the litter removed. Ventilation was provided using an exhaust fan in each room and the ventilation rate was automatically adapted on order to maintain a constant ambient temperature. The air inlet was an opening of 0.34 m^2 connected to a service corridor of the building. Air temperatures of the two experimental rooms and of the service corridor were recorded every hour.

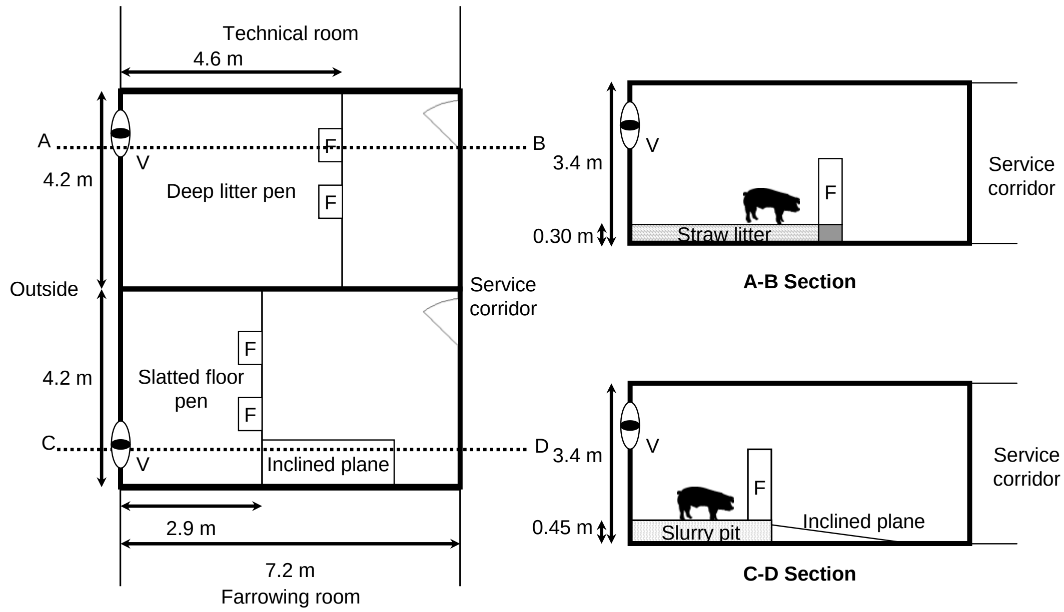

Figure 1 - Plan of the two experimental rooms arranged with slatted floor pen or with the straw based deep litter pen (F: feeder; V: ventilator)

2.2. Animals and feeding

The pigs were cross-bred Piétrain x Belgian Landrace. The five replicates were carried out with two 16-pig groups kept simultaneously on each floor type for a period of four months. The pigs were fed ad libitum with commercial growing meal followed after about 40 days by a finishing meal. The meals were the same for the two groups during the same fattening batch, but differed slightly from one batch to another. Crude protein content ranged from 16.1% to 18.1% for the growing meal and from 15.3% to 17.5% for the finishing meal. The diets were balanced in amino acids. Feeding equipment was composed of two single-spaced feeders per pen with an integrated watering nipple. Meters (Wateau®, EEC approval n° B02 314.29) were used to determine the water consumption per pen. Feed and water intakes and feed conversion ratios were determined per group. The pigs were weighed individually at the beginning and at the end of each batch. At the slaughterhouse, lean meat percentages were measured using the Capteur Gras Maigre (CGM by Sydel, France) and carcass prices were determined individually.

2.3. Measurement of gas emissions

The gas concentrations in the air of the experimental rooms and of the corridor providing fresh air were measured with a 1312 Photoacoustic Multi-Gas Monitor (Innova Air Tech Instruments) equipped to measure NH_3, N_2O, CH_4, CO_2 and H_2O thanks to four filters with absorption wavelengths of 4.4 µm, 4.5 µm, 7.7 µm and 10.6 µm, respectively. During the raising of each batch of pigs, four measurement series of six consecutive days were conducted with a 1-month interval between the series. The first series began 3 weeks after the arrival of the pigs. The sampling of the air in the rooms was performed above the exhaust fan, and the sampling of the air of the corridor at about 1 m from the air inlets. The air was analysed every hour. The ventilation rates were continuously measured by an electronic device (Exavent, Fancom®) and the hourly means were recorded. Emissions (E), expressed as mg/h were calculated according to the following formula:

$$E = D \times (C_i - C_e), (1)$$

with D, the hourly mass flow (kg air per hour), and C_i and C_e, respectively, the concentrations of gas in the air of the room and corridor (mg per kg of dry air). Warming potentials of the greenhouse gases, N_2O, CH_4 and CO_2 together, are expressed in CO_2-equivalents using the following equation:

$$Eq_{CO2}\ (kg.pig^{-1}.day^{-1}) = E_{CO2} + 23\ E_{CH4} + 296\ E_{N2O}, (2)$$

with E_{CO2}, E_{CH4} and E_{N2O} as emissions of CO_2, CH_4 and N_2O ($kg.pig^{-1}.day^{-1}$) (Intergovernmental Panel on Climate Change, 2001).

2.4. Statistical analyses

For each gas and each batch, the differences in the emissions with regard to floor type were tested in the form of a mixed model for repeated measurements with two criteria (SAS® software, proc MIXED) (SAS, 1999): floor type (1 d.f.), period of measurement (3 d.f.) and interaction between floor type and period of measurement with 144 (24 hours x 6 days) successive measurements per period. Residuals were assumed to be normally distributed, with a null expectation. Correlation between successive measurements was modelled using a type 1-autoregressive structure. The combined data obtained with the five batches were treated in the same way as for the previous analysis. Correlation coefficients between each gas emission were determined by linear regression for both floor types with combined hourly data from the five batches (SAS® software, proc REG) (SAS, 1999). Differences between performance and carcass quality of pigs kept on the two floor types were tested using analysis of variance (SAS® software, proc GLM) (SAS, 1999). Differences between characteristics of the slurries from the slatted floor system and litters from the bedded system were tested using the t student test (EXCEL® software, test.student).

3. Results

3.1. Climatic characteristics of the rooms

Regulation of the temperature in the two experimental rooms was more or less similar throughout the experiment (Table 1). The ventilation rate of the room with the deep litter was on average 20% lower than in the room with the slatted floor. This difference between the two rooms is explained by the thermal leakage of the walls being higher in the first one, linked to the positioning of these rooms in the building. So, in order to have a more or less equivalent temperature in the two rooms, the ventilation rate had to be lower in the room with the deep litter. The lower values observed in the 2 rooms with the third replicate can be explained by the lower temperature of the incoming air during this period.

Table 1 – Climatic conditions of the experimental rooms

	Batch					Mean ± s.d.*
	1	2	3	4	5	
Temperature (°C)						
Slatted floor	20.8	20.2	19.4	21.2	21.1	20.5 ± 0.7
Deep litter	21.4	21.0	18.5	21.3	20.9	20.6 ± 1.2
Service corridor	17.2	18.6	12.9	16.5	17.1	16.5 ± 2.2
Outside	10.9	19.2	0.9	11.8	11.8	10.9 ± 6.5
Ventilation (m^3 h^{-1} pig^{-1}						
Slatted floor	78.8	118.0	44.5	83.1	82.6	81.4 ± 26.0
Deep litter	70.7	94.1	29.2	65.1	67.3	65.3 ± 23.3

*: Mean ± s.d. between batches

3.2. Performance of the animals

Pig performance and some parameters of carcass quality are shown in Table 2. Whatever the parameter studied, there was no significant difference between the two floor types.

3.3. Characteristics of the manure

Table 3 presents the characteristics of the manure removed at the end of each fattening period. The differences between the slurry and the litter are statistically significant regarding the amount of manure, dry matter content, pH and nitrogen content ($P<0.05$).

Table 2 - Performance during the fattening of five successive batches of pigs (mean ± s.d. between batches)

	Slatted floor	**Deep litter**
Number of pigs	80	80
Initial weight (kg)	23.8 ± 3.1	23.8 ± 3.0
Final weight (kg)	111.7 ± 4.3	110.1 ± 4.9
Daily weight gain (g)	742 ± 25	729 ± 44
Feed conversion ratio (kg per kg)	3.1 ± 0.1	3.1 ± 0.2
Water drunk (l per pig per day)	4.4 ± 0.5	4.7 ± 0.3
(lper kg of food)	2.0 ± 0.2	2.1 ± 0.1
Lean meat percentage (%)	59.8 ± 0.8	59.9 ± 1.8
Carcass value (EUR per kg live weight)	1.06 ± 0.09	1.04 ± 0.08

Table 3 - Characteristics of manures removed at the end of the five fattening batches

	Batch					**Mean ± s.d.**
	1	**2**	**3**	**4**	**5**	
Amount removed (kg per pig)						
Slurry	185	391	303	354	224	291 ± 86
Litter	139	205	165	270	149	186 ± 54
Dry matter (g per kg of fresh manure)						
Slurry	168	149	170	117	156	152 ± 21
Litter	354	340	287	225	422	326 ± 74
pH						
Slurry	7.57	7.52	7.75	7.18	7.41	7.49 ± 0.21
Litter	8.58	8.12	8.78	8.68	8.44	8.52 ± 0.26
Nitrogen (g per kg of dry matter)						
Slurry	65.4	67.7	48.3	89.8	79.4	70.1 ± 15.6
Litter	18.4	30.0	33.1	46.2	40.0	33.5 ± 10.5

3.4. Gas emissions

Table 4 presents the mean gas emissions during the fattening periods. On average, emissions associated with the deep litter system were significantly higher ($P<0.001$) than from the slatted floor system for NH_3 (+ 110%), N_2O (+ 106%), CO_2 (+ 14%) and H_2O (+ 49%). Only CH_4 emissions did not differ with regard to floor type, with about 16 g emitted per pig and per day. The warming potential of greenhouse gases released from the deep litter system was significantly greater (+18%) than from the slatted floor system (P<0.001). Figure 2 shows the evolution of the emissions from the beginning to the end of the fattening periods. Whatever the gas, emissions were higher at the end in comparison with the beginning (P<0.001). Indeed, mean emissions from both pens were increased by about 5-fold for ammonia, 4-fold for nitrous oxide, 3-fold for methane, and 2-fold for carbon dioxide and water vapour. The increase was regular over the course of time except in the case of nitrous oxide.

Table 4 - Gaseous emissions observed during the fattening of five batches of pigs kept on slatted floor or on straw based deep litter (for each batch, values are means between the four periods of measurement)

	Batch					**Mean ± s.d.***
	1	**2**	**3**	**4**	**5**	
NH_3 (g.pig^{-1}.day^{-1})						
Slatted floor	7.67^a	8.52^a	4.01^a	5.61^a	5.30^a	$6.22^a \pm 1.84$
Deep litter	17.13^b	12.11^b	11.75^b	11.69^b	12.82^b	$13.10^b \pm 2.30$
N_2O (g.pig^{-1}.day^{-1})						
Slatted floor	0.33^a	0.37^a	0.37^a	0.32^a	1.32^a	$0.54^a \pm 0.44$
Deep litter	0.41^b	0.66^b	1.33^b	0.44^b	2.73^b	$1.11^b \pm 0.98$
CH_4 (g.pig^{-1}.day^{-1})						
Slatted floor	18.18^a	17.84	12.25^a	17.06^a	16.28	16.32 ± 2.39
Deep litter	13.94^b	16.73	17.48^b	15.59^b	16.42	16.03 ± 1.35
CO_2 (kg.pig^{-1}.day^{-1})						
Slatted floor	1.85	2.01	1.56^a	1.67^a	1.60^a	$1.74^a \pm 0.19$
Deep litter	1.98	1.96	1.88^b	2.05^b	1.99^b	$1.97^b \pm 0.06$
Eq_{CO2} (kg.pig^{-1}.day^{-1})**						
Slatted floor	2.36	2.38	1.95^a	2.16^a	2.37^a	$2.24^a \pm 0.84$
Deep litter	2.43	2.40	2.68^b	2.54^b	3.18^b	$2.64^b \pm 0.97$
H_2O (kg.pig^{-1}.day^{-1})						
Slatted floor	2.72^a	2.72^a	2.05^a	2.53^a	2.40^a	$2.48^a \pm 0.28$
Deep litter	3.67^b	3.37^b	3.33^b	3.99^b	4.13^b	$3.70^b \pm 0.36$

*: Mean ± s.d. between batches

**: Eq_{CO2}: Warming potentials of N_2O, CH_4 and CO_2 together, expressed in equivalent-CO_2

[a,b]: For each gas, values in the same column with the different subscripts differ significantly (P<0.05) regarding to floor type

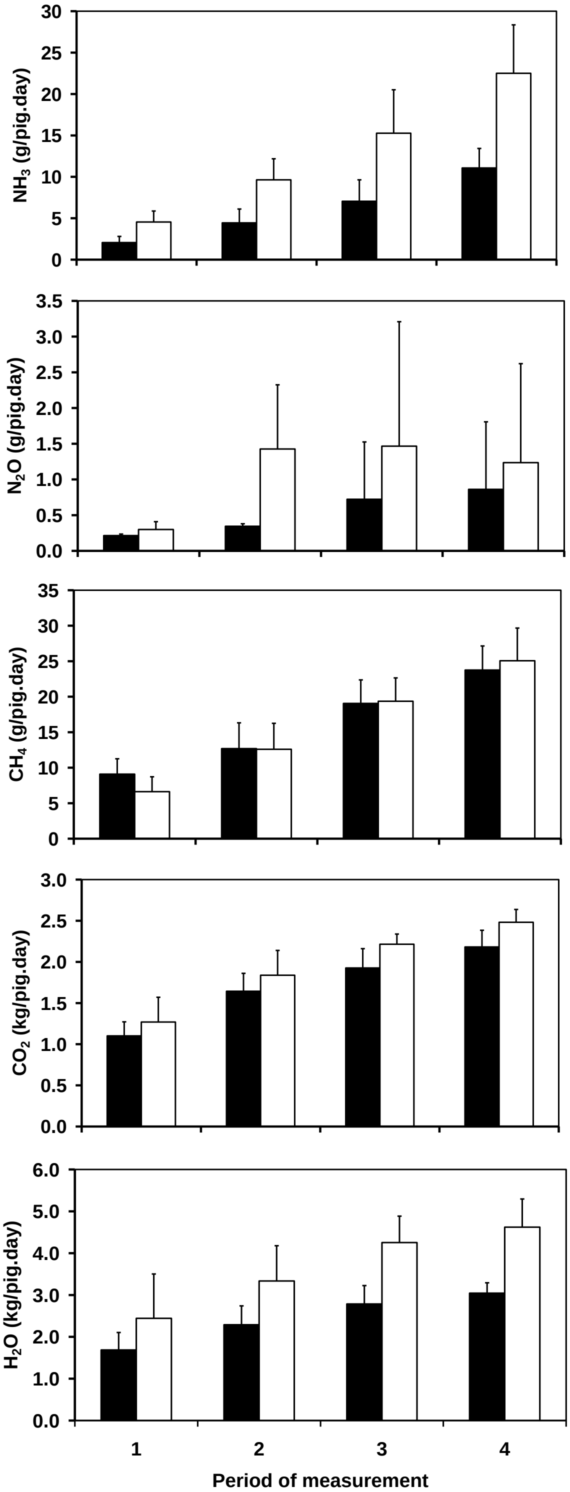

Figure 2 - Evolution of emissions of ammonia, nitrous oxide, methane, carbon dioxide and water vapour throughout fattening period pigs kept on slatted floor (closed bars) or on straw based deep litter (open bars). For each period of measurement, means with s.d. between the five batches. According to a constant daily gain of about 735 g per day, the body weight of pigs were on average 41 kg, 63 kg, 85 kg, 107 kg for the four successive measurement periods, respectively.

Table 5 presents correlation coefficients between gas emissions. All were significant. Maximal values were obtained between carbon dioxide and water vapour for litter and between ammonia and methane for the slatted floor. Minimal values were obtained between nitrous oxide and other gases.

Table 5 - Correlation coefficient between emissions of ammonia, nitrous oxide, methane, carbon dioxide and water vapour during the fattening of five successive batches of pigs on slatted floor or on straw based deep litter

	Slatted floor				Deep litter			
	NH_3	N_2O	CH_4	CO_2	NH_3	N_2O	CH_4	CO_2
N_2O	0.33	/	/	/	0.15	/	/	/
CH_4	0.77	0.28	/	/	0.67	0.27	/	/
CO_2	0.76	0.35	0.71	/	0.78	0.26	0.78	/
H_2O	0.58	0.26	0.59	0.76	0.75	0.25	0.69	0.89

4. Discussion

The mean ammonia emission from the slatted floor room, i.e. 6.22 g per pig per day, is close to the lowest values cited in the literature, which range from 4 – 6 g to about 14 g (Groot Koerkamp et al., 1998; Robin et al., 1998; Fernandez et al., 1999; Nicholson et al., 2000; Balsdon et al., 2001; Guingand and Granier, 2001; Kermarrec and Robin, 2002; CORPEN, 2003; European Pollutant Emission Register, 2003; Guingand, 2003). In the current study, water supplied in the slurry pit before the arrival of the animals and the cleanliness of the slatted floor and the pigs had certainly contributed to the low values recorded.

The mean ammonia emission from the deep litter room, i.e. 13.1 g per pig per day, is within the range of data from the literature. According to the European Pollutant Emission Register (2003), ammonia emissions from fattening pigs kept on straw based litter recorded in Denmark, the United Kingdom and Germany were 8.7, 10.6 and 15.6 g per pig per day, respectively. In a previous experiment, Nicks et al. (2004) obtained ammonia emissions of 13.6 g per pig per day during the fattening of three successive batches on the same straw litter. Nicholson et al. (2000) and Balsdon et al. (2001) observed higher emission factors, with 18.4 and 19.9 g per pig per day, respectively.

Important variations in ammonia emissions are related in literature, whatever the floor type, in relation to diversity in housing conditions and management. Some influencing factors are: animal density, initial and final weight of pigs, feed management, waste treatment, removal/storage system, cleaning system, interior climate, the season and for each system in particular, the kind of slatted floor and the amount of straw supply (Andersson, 1996; Groot Koerkamp et al., 1998; Møller et al., 2000; United Nations, 2001; Robin et al., 2004; Hassouna et al., 2005; Nicks, 2006).
Few data regarding the comparison, in standardized conditions, of ammonia emissions from the deep litter system and the slatted floor system are available. The current comparison between the two floor types shows a 110% higher rate of emission during the fattening of pigs on straw based deep litter than on the slatted floor. Nicholson et al. (2000) and Balsdon et al. (2001) also observed greater emissions, from +30% to +70%, with straw based deep litter. According to Andersson (1996), a combination of high temperature and high pH, both observed in litter, leads to considerable ammonia emissions.

Nitrous oxide is a by-product of nitrification and denitrification processes which normally convert ammonia into inert dinitrogen gas. Nitrification requires aerobic conditions and denitrification requires anaerobic conditions. Both conditions can be found in deep litter but not in slurry. However, emissions from manure on the floor can occur in pig houses with slatted floors. According to our results, there are two times more emissions from pig houses with deep litters (1.11 versus 0.54 g per pig per day, respectively) but variations from one batch to the other were high whatever the floor type. Data from the literature confirm the large range of variation in N_2O emissions. For piggeries with deep litter systems, emissions range from 0.03 g to about 8 g per pig per day (Robin et al., 1999; European Commission, 2003; Nicks et al., 2004; Hassouna et al., 2005). With slatted floor systems, data range from 0.17 g to about 2.26 g per pig per day (Osada et al., 1998; Robin et al., 1998; European Commission, 2003).

Methane originates from enteric fermentation by animal and anaerobic degradation of organic components in manure. Methane from manure is produced under anaerobic conditions and is enhanced by high temperature (Sommer and Møller, 2000). Data in the literature show considerable variations, from about 2 to 30 g per pig per day in pig houses with slatted floors (Groot Koerkamp and Uenk, 1997; European Commission, 2003; Gallmann et al., 2003; Godbout et al., 2003; Guarino et al., 2003; Haeussermann et al., 2006). Few data are available concerning emissions with fattening pigs on deep litter. Stout et al., (2003) reported a mean emission of 2.77 g per pig per day and, during a previous experiment, Nicks et al. (2004) obtained on average 7.39 g per pig per day during three fattening periods on the same straw based deep litter. In this study, methane emissions did not differ in relation to the floor type, with a mean value of 16 g per pig per day.

Carbon dioxide production was greater (+14%) from the room with straw based deep litter than from the room fitted with the slatted floor. CO_2 from piggeries has two main origins: animal respiration and manure fermentation. CO_2 exhalation is estimated to be about 1.5 – 1.7 kg per day for a 65-kg pig (Ni et al., 1999a; CIGR, 2002). Therefore, the CO_2 manure production can be estimated to about 150 g and 350 g per pig per day from slurry and litter, respectively. On partly slatted floor, Ni et al. (1999b) estimated production from slurry at about 540 g per pig per day. On deep litter, Jeppsson (2000) found a total production of about 1.6 kg per pig per day and a production from straw litter of about 460 g per pig per day. CO_2 production is often used for the calculation of the ventilation rate in naturally ventilated animal houses. Usual estimations are based on heat production by animals (CIGR, 2002). Emissions observed here show that releases from manure also have to be taken into account in order to avoid imprecision of ventilation rate estimation. Indeed, in the current experiment, manure would have produced about 10% and 20% of total emissions with slatted and bedded system, respectively.

Water vapour emissions were greater (+49%) during the fattening on straw-based deep litter than on the slatted floor. The two main origins of water vapour in a piggery are production by animals and release from manure. According to the CIGR (2002), with a room temperature of 20.5 °C, a 65 kg-pig would produce about 2.72 kg of water vapour per day. Emission rates observed in this study with the slatted floor show that production from slurry should be considered as negligible, as reported by de Oliveira et al. (1999). By contrast, release from deep litter was significant and could be estimated to be 1.0 kg per pig per day, representing a weight loss of around 120 kg at the end of the fattening period to be removed by the manure. Water consumption was relatively similar between the two systems and could not explain the difference completely.

Rather, greater emissions are due to the high temperature observed in litter due to fermentation. Emission rates reported in the literature with straw based deep litter range from 2.7 to 5.2 kg per pig per day (Robin et al., 1999; Jeppsson, 2000; Nicks et al., 2004). As water vapour emissions are higher with the deep litter system, this system needs higher ventilation rates in "winter conditions" when air relative humidity is the key factor determining the ventilation rate.

In conclusion, although rearing pigs on straw generally has a good brand image for the consumer, this rearing system produces more pollutant gases than keeping pigs on slatted floors. Ammonia and nitrous oxide emissions are doubled and carbon dioxide emissions are 14% greater. Methane emissions are similar whatever the floor type. According to the warming potentials of greenhouse gases, rearing pigs on litter would emit 18% more of CO_2-equivalents, i.e. 2.64 versus 2.24 kg per pig per day.

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2. EMISSIONS D'AMMONIAC ET DE GAZ A EFFET DE SERRE ASSOCIEES A L'ELEVAGE EN GROUPE DE TRUIES GESTANTES SUR CAILLEBOTIS OU SUR LITIERE DE PAILLE ACCUMULEE

Depuis 2013, la législation européenne (Directive 2008/120/CE), en intégrant des considérations de bien-être animal, impose de loger les truies gestantes en groupe depuis 4 semaines après l'insémination jusqu'à une semaine avant la mise-bas. Cette législation exige également l'accès permanent pour les animaux à des matériaux permettant des activités de recherche et de manipulation. Dans ce contexte, l'élevage de truies gestantes sur litière paillée pourrait susciter un regain d'intérêt. Alors que les attentes sociétales en terme environnemental sont grandissantes, peu d'études traitent de l'impact de ce type d'hébergement sur le milieu. C'est pourquoi cette étude a pour objectif de comparer les émissions de NH_3 et de GES (N_2O, CH_4 et CO_2) lors de l'élevage en groupe de truies gestantes sur sol à caillebotis total ou sur litière de paille accumulée.

Pour cette étude, deux locaux identiques en volume (103 m^3) et en surface (30 m^2) ont été équipés d'une loge permettant d'héberger un groupe de 5 truies gestantes. Les loges étaient composées d'une zone d'alimentation et d'une zone de repos. La zone d'alimentation consistait en 5 cages individuelles (1,2 m^2/truie) disposées sur un sol bétonné et dont l'accès était limité aux périodes de repas (1 repas d'une heure par jour). La zone de repos avait une surface de 12,6 m^2 (2,5 m^2 $truie^{-1}$) dont le sol était constitué d'un caillebotis total en béton (pourcentage de vide 15%) dans un local, et d'une litière de paille accumulée dans l'autre. Avant l'arrivée des animaux, 700 L d'eau ont été déversés dans la fosse à lisier afin d'éviter la formation précoce d'une croûte et de faciliter l'évacuation des lisiers en fin d'engraissement ; et 100 kg de paille de blé entière ont été disposés sur le sol de la loge paillée afin de constituer la couche initiale de litière d'une épaisseur de 25-30 cm. Par la suite, 25 kg de paille ont été apportés une fois par semaine pour atteindre 300 kg en fin de gestation. Trois bandes successives de 10 truies gestantes de race Landrace belge, réparties uniformément en deux groupes en fonction de la parité, du poids et de l'épaisseur de lard dorsal, ont été hébergées dans ces locaux depuis 7 semaines après insémination jusque 7 jours avant la date prévue de mise-bas. Le temps de séjour des truies a été de 65,3 jours en moyenne. Après le départ de chaque bande de truies, les effluents (lisiers et fumiers) étaient évacués et les loges étaient nettoyées. La ventilation des locaux se faisait au moyen de ventilateurs extracteurs (un par local) et de manière contrôlée avec adaptation automatique du débit de ventilation en fonction de la température, ces deux paramètres étant mesurés et enregistrés en continu (Fancom, Panningen, Pays-Bas). Les concentrations en gaz ont été mesurées dans les locaux expérimentaux et dans le couloir d'apport d'air par détection photo-acoustique infrarouge au moyen d'un moniteur équipé pour la mesure simultanée de NH_3, N_2O, CH_4, CO_2 et H_2O (1412 Photoacoustic Multi-Gas Monitor, Innova Air Tech Instruments, Nærum, Denmark). Trois séries de mesures de six jours consécutifs réparties de manière homogène sur la période de gestation ont été réalisées pour chaque bande de truies. Les émissions (E_{gaz}) ont été calculées sur base horaire grâce à l'équation suivante :

$E_{gaz} = D \times (C_i - C_e)$,

avec D, le débit de ventilation (kg air h^{-1}), et C_i et C_e, respectivement la concentration en gaz dans l'air du local expérimental et du couloir d'apport d'air (mg kg^{-1} air). Les résultats d'émissions ont été testés au moyen d'un modèle mixte pour données répétées (SAS, Mixed Proc) en incluant l'effet du type de sol (1 dl), de la série de mesure (2 dl), de l'interaction sol-série (2 dl) et du lot comme effet aléatoire (2 dl) avec 144 données (24 heures x 6 jours) par série de mesure.

Les émissions de NH_3 ont été réduites avec le logement sur litière de paille accumulée en comparaison au logement sur sol à caillebotis (9,05 *versus* 12,77 g NH_3 truie^{-1} jour^{-1}, $P<0,001$). Ce résultat contredit ce qui avait été observé dans l'étude précédente avec les porcs charcutiers. Parmi les facteurs pouvant expliquer cette discordance, on retrouve les effets de la surface disponible et de la quantité de paille apportée. En effet, il est généralement admis que les émissions de NH_3 sont proportionnelles à la surface d'émission (Monteny et Erisman, 1998). Les porcs charcutiers élevés sur litière disposaient de 58% d'espace en plus en comparaison à leurs homologues élevées sur caillebotis (1,20 *versus* 0,76 m^2 par porc) alors que les truies gestantes disposaient de la même surface avec les deux types de sol (2,5 m^2 par truie). Le taux de paillage différait également entre porcs charcutiers et truies gestantes (390 g jour^{-1} porc^{-1} *versus* 920 g jour^{-1} truie^{-1}) alors que la quantité d'azote excrétée par individu est équivalente pour les deux types d'animaux et estimée à environ 40 g N jour^{-1}. Un paillage plus important augmente le rapport C/N des fumiers, ce qui favorise la croissance bactérienne et l'assimilation d'azote en protéines bactériennes plus stables, limitant ainsi la synthèse de NH_3 (Dewes, 1996; Sommer et Moller, 2000). La vérification de ces hypothèses fera l'objet des deux chapitres suivants.

Les émissions de N_2O ont été plus élevées avec le sol paillé en comparaison au sol latté (2,27 *versus* 0,47 g N_2O truie^{-1} jour^{-1}, $P<0,001$) confirmant ainsi les résultats précédents obtenus avec les porcs charcutiers. L'environnement hétérogène rencontré au sein des litières alliant conditions aérobies et anaérobies favorise la production de N_2O durant les processus de nitrification/dénitrification (Poth and Focht, 1985). A l'inverse, le caractère strictement anaérobie des lisiers limite les émissions de N_2O.

Les émissions de CH_4 à partir des loges paillées ont été légèrement réduites par rapport aux loges à caillebotis (9,20 *versus* 10,12 g CH_4 truie^{-1} jour^{-1}, $P<0,001$). La production entérique, qui est fonction de la quantité de fibres ingérées, est évaluée à environ 7,5 g CH_4 truie^{-1} jour^{-1} pour les deux types de logement (Philippe et al., 2008). Cette estimation ne tient pas compte de l'ingestion potentielle de paille par les truies élevées sur litière, ce qui augmenteraient la production digestive de CH_4. Les émissions totales étant plus faibles avec le système paillé, cela suppose une production réduite dans les litières en comparaison au lisier. Le caractère plus aéré des fumiers contribue à y limiter la méthanogenèse qui est un phénomène strictement anaérobie (Yamulki, 2006).

Les émissions de CO_2 ont été plus élevées avec le système paillé (2,83 versus 2,41 kg CO_2 truie^{-1} jour^{-1}, $P<0,001$), comme observé avec les porcs charcutiers. La source principale est le CO_2 respiratoire qui est fonction du métabolisme des animaux et donc du taux d'activité, du poids corporel, des consommations alimentaires et de la température ambiante (CIGR, 2002 ; Pedersen et al., 2008). Ces paramètres ayant été semblables avec les deux modes de logement, on peut estimer que la production respiratoire a été similaire pour les groupes comparés. Les réactions de compostage au sein des fumiers sont proposées comme responsables des niveaux d'émission plus élevés.

En conclusion, pour des truies gestantes élevées en groupe, le système d'hébergement sur litière de paille accumulée testé dans cette étude a été associé à des émissions réduites de NH_3 par rapport au système sur caillebotis, ce qui est contraire aux résultats obtenus précédemment avec les porcs charcutiers. Les hypothèses avancées pour expliquer cette contradiction (effet de la surface et du taux de paillage) seront testées lors des deux études suivantes. Concernant les GES, la légère réduction des émissions de CH_4 est largement compensée par une augmentation des émissions de N_2O et CO_2.

Ammonia and greenhouse gas emission from group-housed gestating sows depends on floor type

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Abstract

The ban by 2013 in the EU of individual accommodations for gestating sows and the renewed interest for litter systems could promote in the future the group-housing of gestating sows on litter. But, what about the environmental impacts of this rearing technique? To answer this question, a study was scheduled to quantify pollutant gases emissions (nitrous oxide, N_2O; methane, CH_4; carbon dioxide, CO_2 and ammonia, NH_3)according to floor type in the raising of group-housed gestating sows. Three successive batches of 10 gestating sows were used for this trial. Each batch was divided into 2 homogeneous groups randomly allocated to a treatment: concrete slatted floor or straw-based deep litter. The groups were separately kept in two identical rooms equipped with a pen divided in a lying area (slatted floor or deep litter) and five individual feeding stalls. The feeding stalls were equipped with front feeding troughs and rear gates preventing the access to the stalls outside of the feeding time.

Between each batch, the pens were cleaned. In both rooms, ventilation was automatically adapted to maintain a constant ambient temperature. The gas emissions were measured 3 times (weeks 2, 5 and 8 of stay) during 6 consecutive days by infra red photoacoustic detection.

Sows performance (body weight gain, backfat thickness, number and weight of piglets) was not significantly different according to the floor type. With sows kept on slatted floor and compared to sows housed on straw-based deep litter, gaseous emissions were significantly greater for NH_3 (12.77 *vs.* 9.05 g d^{-1} sow^{-1}; $P<0.001$) and CH_4 (10.12 *vs.* 9.20 g d^{-1} sow^{-1}; $P<0.01$), and significantly lower for N_2O (0.47 *vs.* 2.27 g d^{-1} sow^{-1}; $P<0.001$), CO_2 equivalents (0.44 *vs.* 0.94 kg d^{-1} sow^{-1}; $P<0.001$) and CO_2 (2.41 *vs.* 2.83 kg d^{-1} sow^{-1}; $P<0.001$). There was no significant difference for water vapour emissions (3.25 *vs.* 3.21 kg d^{-1} sow^{-1}; $P>0.05$).
In conclusion, the main environmental disadvantage of the deep litter system pointed in this study was the greater N_2O-emissions and thus, the greater CO_2eq-emissions, compared to slatted floor. However, the use of deep litter was related to reduced NH_3- and CH_4-emissions.

1. Introduction

The development of intensive pig production has been associated with the use of slatted floor and, for gestating sows, of individual cages. Currently, the European legislation includes welfare considerations for the design of the stall. So, the Directive 2001/88/CE imposes by 2013 to keep gestating sows in group at least from 4 weeks after insemination till 1 week before farrowing. Concurrently, there is a renewed interest for the litter system due to animal welfare improvement (Tuyttens, 2005) and odour nuisance reduction (Kaufmann, 1997) related to this system. These factors could thus promote the group-housing of gestating sows on litter, although the litter system is associated with increased cost related to the straw use and the labour for litter management (Laligant *et al.*, 2002; Nicks, 2004). Furthermore, the real impact of the litter system on the environment has still to be assessed, and particularly the emissions of pollutant gases such as ammonia (NH_3) and greenhouse gases (GHG). Indeed, the protocols of Göteborg (United Nations Economic Commission for Europe (UNECE), 2007) and of Kyoto (Monteny *et al.*, 2006) aim to quantify and reduce NH_3- and GHG-emissions. However, for gestating sows, there is a lack of data concerning the comparison under standardized and field conditions of the gaseous emissions according to floor systems.
NH_3-emissions contribute to soil and water acidification and eutrophication and to indirect emissions of nitrous oxide (N_2O) (Intergovernmental Panel on Climate Change (IPCC), 2006). In Europe, approximately 80% of NH_3 production originates from

livestock facilities (Reidy *et al.*, 2009). Furthermore, NH_3 is well known as a toxic gas, irritating the respiratory tract at concentrations exceeding 15 ppm (Banhazi *et al.*, 2008).

The GHG associated with livestock production are carbon dioxide (CO_2), methane (CH_4) and N_2O. Among these gases, N_2O contributes also to the destruction of the ozone shield. N_2O and CH_4 are important contributors because their global warming potential (GWP) over a 100-years period are 298 and 25 times that of CO_2 (IPCC, 2007). For CO_2, one can estimate usually that livestock production is compensated by consumption by photosynthesis of plants used as feed. However, CO_2-emissions might differ from one rearing system to another as shown for example for weaning and fattening pigs (Philippe *et al.*, 2007a, 2007b; Cabaraux *et al.*, 2009). Besides, CO_2-production by animals and waste is an essential parameter for ventilation rate estimation using a mass balance method (Pedersen *et al.*, 2008).

Water vapour (H_2O) production may also be used for ventilation rate estimation (Blanes and Pedersen, 2005). Furthermore, determination of H_2O emission is a key factor in specifying ventilation rates in order to avoid excessive indoor relative humidity in livestock buildings, especially with bedded systems (CIGR, 2002).

Therefore, the aim of this study was thus to quantify gaseous emissions of NH_3, N_2O, CH_4, CO_2 and H_2O in the raising of group-housed gestating sows according to the floor type (concrete slatted floor or straw-based deep litter).

2. Materials and methods

The trial was carried out in experimental rooms located at the Faculty of Veterinary Medicine of Liège University (Belgium). The ethical committee of the university approved the use and treatment of animals in this study.

2.1 Experimental rooms

Two experimental rooms, similar in volume (103 m^3) and surface (30.2 m^2), were arranged and equipped for this experiment. Rooms consisted of a service area and a pen to house a group of five gestating sows. Pens were divided in a lying area (12.6 m^2, i.e. 2.5 m^2 per sow) and five individual feeding stalls (figure 1). The feeding stalls were equipped with front feeding troughs and rear gates preventing the access to the stalls outside of the feeding time.

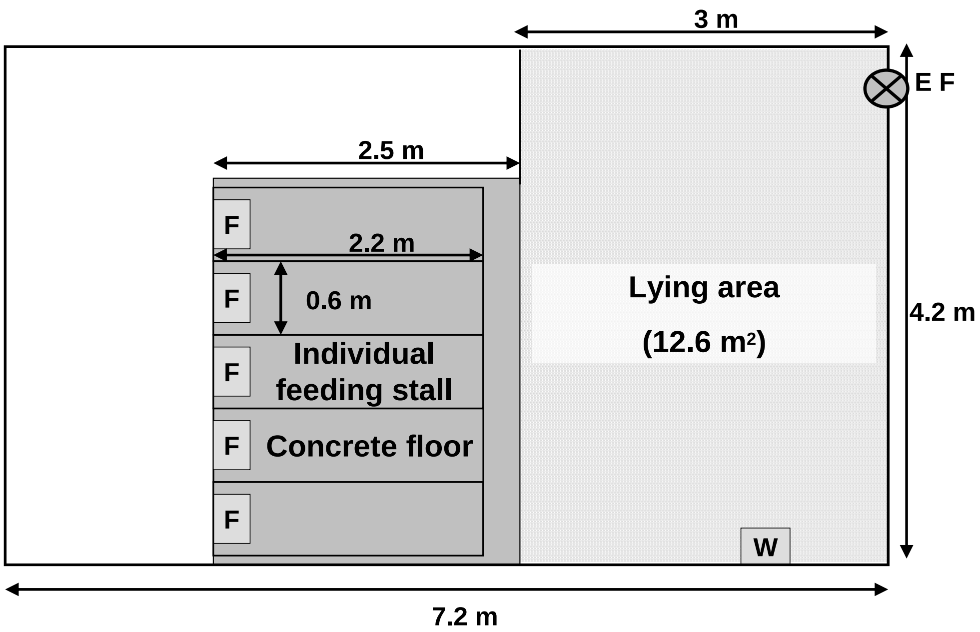

Figure 1 - Plan of the experimental rooms (F: feeding trough; W: water trough; EF: exhaust fan)

In room 1, the lying area was constituted of a concrete slatted floor and was at the same level that the feeding stalls. To meet the EU recommendations (directive 2001/88/CE), a part of the lying area (1.3 m^2 per sow) was built with an 18 mm opening between two slats, i.e. with a void percentage of 14.2%, the remaining part (1.2 m^2 per sow) being built with an 20 mm opening between two slats, i.e. with a void percentage of 15.8%. The slurry pit was only under the lying area and was 30 cm deep. Just before the arrival of the sow, 700 l water were poured into the pit to have a 5-6 cm water layer in order to avoid crust formation and to ensure a good homogenisation of the slurry in the pit at the very beginning.

In room 2, the lying area was a deep litter. Just before the arrival of the animals, about 100 kg of whole wheat straw were used to constitute the initial deep litter of about 25-30 cm depth. Thereafter, each Monday, 25 kg straw were added to the litter. The feeding stalls were raised the height of 30 cm.

After each batch, the manures were removed and the pens were cleaned. The manures were weighedand sampled after homogenisation (two samples per room and per batch). The samples were analysed to determine the contents of dry matter, organic matter, total N (Kjeldahl method) and ammonium ions (NH_4^+), using standard NEN methods for manure (Schulten, 1998a-d).

Each room was ventilated with an exhaust fan (Fancom, Panningen, The Netherlands) and the ventilation rate was adapted automatically to maintain a constant ambient temperature by means of regulator FCTA (Fancom, Panningen, The Netherlands). Fresh air entered through an opening of 0.34 m^2 which was connected to the service corridor of the building; the outside air was thereby preheated before entering the experimental rooms. The air temperatures of the experimental rooms, the corridor and the outside were measured automatically every hour. The ventilation rates were measured continuously with an Exavent apparatus (Fancom, Panningen, The Netherlands) with accuracy of 35 m^3/h, i.e. 1% of the maximum ventilation rate of the fan. The hourly means were recorded.

2.2. Animals and feed

Three successive batches of 10 Belgian Landrace gestating sows were used. They were divided into 2 homogeneous groups of 5 animals according to the parity, the body weight and the backfat thickness. Each group was randomly allocated to a treatment: stay in room 1 on concrete slatted floor (SL) or in room 2 on straw-based deep litter (DL). About seven weeks after service, the gestating sows arrived in the experimental rooms and 7 days prior to giving birth, they moved to farrowing pens; the stay duration was thus 9 weeks for each batch.

The sows received a commercial conventional gestation diet based on cereals (Table 1). The amounts of daily feed were restricted and determined per sow as function of parity and backfat thickness. The feed was supplied once a day at 08:00 am and the sows were blocked in individual feeding stalls during the feeding time (1 h). There was a water trough with *ad libitum* access in each pen.

Individually, the sows were weighed and the backfat thickness was measured on P2-site by ultrasonography (Dourmad *et al.*, 2001) at the beginning and at the end of the trial period. The feed and water intakes were recorded per group and per batch. The number of piglets born alive and stillborn was recorded.

Table 1 - Composition of diet (as-fed basis)

Ingredient (%)	
Barley	23.7
Wheat	22.0
Wheat bran	12.7
Corn	12.0
Sugar beet pulp	4.3
Chicory pulp	1.0
Sugar-beet molasses	0.6
Extracted sunflower meal	5.3
Extracted palm kernel meal	4.0
Extracted rapeseed meal	4.0
Expeller rapeseed meal	1.1
Soybean shell	2.7
Linseed	1.0
Corn gluten feed	0.5
Animal fat	2.0
Calcium carbonate	1.4
Chemical composition (%)	
Moisture	12.4
Crude protein	13.0
Crude fat	4.9
Crude ash	5.4
Crude fibre	7.8
Starch	35.5
Sugar	3.7
NSP[1]	25.0
Total phosphorus	0.5
Lysine	0.7
Net Energy ($kJ\ kg^{-1}$)	8876

[1]Non-starch polysaccharides, calculated as DM − (CP + crude fat + crude ash + starch + sugar)

2.3. Gas emissions measurement

The concentrations of gases in the experimental rooms and in the corridor supplying fresh air were measured by infrared photoacoustic detection with a Photoacoustic Multi-gas Monitor - INNOVA 1412 (LumaSense Technologies A/S, Ballerup, Denmark) equipped and calibrated for simultaneous measurement of NH_3, N_2O, CH_4, CO_2 and H_2O. The lower levels of detection were 0.2 ppm for NH_3, 0.03 ppm for N_2O, 0.1 ppm for CH_4 and 3.4 ppm for CO_2, with an accuracy rate of 95%. The air was sampled just upstream of the exhaust fan in the experimental rooms and at 1 m from the air inlets in the corridor. For each batch, the concentrations were measured 3 times (weeks 2, 5 and 8 of stay) during 6 consecutive days. The Multi-gas monitor was programmed by conducting a cycle of 3 measurements every hour, once every 20 min, the air being sampled successively in the 2 experimental rooms and the corridor.

For each gas, the emissions (E_{gas}) were calculated on an hourly basis and expressed in mg h^{-1} using the following formula:

$$E_{gas} = D \times (C_{in} - C_{out})$$

with D, the hourly mass flow (kg air h^{-1}); C_{in} and C_{out}, the concentrations of gas in the air of the room and corridor respectively (mg kg^{-1} air). The mean emissions per day and per sow were calculated for each series of measurements.

The GWP of the GHG, N_2O and CH_4 together, was expressed in CO_2 equivalents (CO_2eq). CO_2-emissions were excluded from this estimation because IPCC (2006) estimated that CO_2 production by livestock is compensated by CO_2 consumption by photosynthesis of plants used as feed. However, indirect N_2O-emissions from atmospheric deposition of nitrogen (N) from NH_3 on soils and water surfaces have been added to the direct N_2O-emissions. The indirect emissions were calculated considering an emission of 0.01 kg N_2O-N kg^{-1} emitted NH_3-N (IPCC, 2006). The emissions of Eq_{CO2} (kg d^{-1} sow^{-1}) were thus calculated using the following equation:

$$E_{CO2eq} = 25\ E_{CH4} + 298\ (E_{N2O} + 44/28\ (0.01\ E_{NH3\text{-}N})\ )$$

taking into account that the warming potentials of CH_4 and N_2O over a 100-year period are, respectively, 25 and 298 times that of CO_2 (IPCC, 2007). This estimation considers the emissions from the building but not the emissions related to the storage and the spreading.

2.4 Nitrogen balance

Nitrogen balance (g N day^{-1} sow^{-1}) was calculated for each group with inputs corresponding to N-straw and N-feed intakes and outputs corresponding to N-content of waste and N from gaseous emissions of NH_3 and N_2O. N-straw was determined from samples analysis (one sample par batch) by Kjeldahl method. N-feed values were based on diet composition and consumption by sows. The determination of N-waste, NH_3-N and N_2O-N were above-described. N-retention was estimated as a part of N-feed. According to Philippe *et al.* (2008), N-retention coefficient can be estimated at 15%. Unaccounted-N was obtained by subtraction of N-retention and N-outputs from N-inputs.

2.5. Statistical analyses

For animal performance data recorded per sow, the differences between groups housed on 2 different floors (SF *vs.* DL) were tested using analysis of variance with 2 criteria (proc GLM) (SAS, 2005): floor (1 df), batches (2 df) and interaction between floor and batches. For intakes data, manure characteristics and N balance, recorded per pen, the differences were tested in the same way but with only floor (1 df) as criterion (proc GLM) (SAS, 2005).

For room temperatures, ventilation rates and gas emissions, the combined data from the 3 batches were tested in the form of a mixed model for repeated measurements (proc MIXED) (SAS, 2005) including the effects of the floor (1 df), the week of measurement (2 df), the interaction between the floor and the week of measurement (2 df) and the batch as random effect (2 df), with 144 (24 h × 6 d) successive measurements per week. Residuals were normally distributed, with a null expectation (proc UNIVARIATE) (SAS, 2005). Correlation between successive measurements was modelled using a type 1-autoregressive structure.

3. Results

3.1. Climatic characteristics of the rooms

The data about the air temperatures and the ventilation rates are shown in Table 2. The differences between experimental rooms were not statistically significant (P>0.05). The average temperatures of the air were 20.2 °C in the experimental rooms, 18.3 °C in the service corridor and 15.3 °C outside. The mean ventilation rate was 295 m^3 h^{-1} per sow.

Table 2 - Climatic characteristics of the experimental rooms

	Batch			
	1[a]	2[a]	3[a]	Mean[b]
Temperatures (°C)				
SF	19.3 ± 0.4	22.3 ± 0.9	19.2 ± 0.3	20.3 ± 1.7
DL	19.1 ± 0.5	22.1 ± 1.0	18.9 ± 0.3	20.0 ± 1.8
Service corridor	17.0 ± 1.1	20.9 ± 1.0	17.0 ± 0.7	18.3 ± 2.2
Outside	12.5 ± 0.9	19.1 ± 0.4	14.3 ± 2.1	15.3 ± 3.4
Ventilation rates (m^3 h^{-1} sow^{-1})				
SF	233.9 ± 33.8	450.4 ± 23.6	210.6 ± 24.7	298.3 ± 132.2
DL	222.7 ± 37.9	437.7 ± 24.2	211.9 ± 25.6	290.7 ± 127.4

SF: room with sows kept on concrete Slatted Floor; DL: room with sows kept on straw-based Deep Litter; [a] Mean ± standard deviation between the 3 periods of measurements; [b] Mean ± standard deviation between mean values of the 3 batches

3.2. Animal performance

The performance is presented in Table 3. There were no significant differences between groups according to the floor type for animal performance. The mean initial and final body weight were respectively 193 kg and 229 kg with an average body weight gain of 35.5 kg and an average feed intake of 2.48 kg d^{-1}. The mean initial and final backfat thicknesses were respectively 16.3 mm and 18.8 mm, with a backfat thickness gain of 2.5 mm. On average, each sow gave birth to 13.3 piglets of which 12.4 were alive.

Table 3 - Performance of gestating sows as influenced by the floor type, slatted floor (SF) or straw-based deep litter (DL) (mean ± standard deviation between the 3 batches)

	SF	DL
Number of sows	15	15
Parity	3.7 ± 1.6	3.4 ± 0.9
Initial body weight (kg)	194.7 ± 15.3	191.5 ± 11.8
Final body weight (kg)	228.4 ± 7.9	228.8 ± 7.9
Body weight gain (kg)	33.7 ± 9.2	37.3 ± 8.9
Feed intake (kg d^{-1})	2.48 ± 0.02	2.49 ± 0.06
Water intake per sow		
l d^{-1}	5.09 ± 0.69	5.97 ± 0.79
l kg^{-1} ingested feed	2.05 ± 0.29	2.39 ± 0.27
Initial backfat thickness (mm)	15.9 ± 1.6	16.7 ± 1.3
Final backfat thickness (mm)	18.7 ± 2.5	18.8 ± 0.2
Backfat thickness gain (mm)	2.8 ± 2.6	2.1 ± 1.2
Number of born piglets		
Alive	11.9 ± 0.4	12.9 ± 3
Stillborn	1.1 ± 0.8	0.5 ± 0.6
Total	13.1 ± 0.8	13.4 ± 3.5

3.3. Amounts and composition of waste

In the room with deep litter, the mean amount of supplied straw was 0.9 kg d^{-1} sow^{-1} (Table 4). The amount of waste was not significantly different between slurry and straw-manure with about 3.4 kg d^{-1} sow^{-1}. However, the amount of collected DM was higher with the straw-based system (935 *vs.* 385 g d^{-1} sow^{-1}; $P<0.001$). With the use of a slatted floor rather than a deep litter, the waste had a significantly lower pH (-0.71 unit; $P<0.01$) and a significantly greater NH_4^+-N content expressed per day and per sow (+162%; $P<0.001$). NH_4^+-N represented 40% of the total N excreted per day and per sow in slurry versus 12% in deep litter.

Table 4 - Manure characteristics as influenced by the floor type - concrete slatted floor (SF) or straw-based deep litter (DL)- in gestating sows (mean ± standard deviation between the 3 batches)

	SF	**DL**	**Significance**
Supplied straw (kg d^{-1} sow^{-1})	-	0.92 ± 0.06	-
Collected waste			
kg d^{-1} sow^{-1}	3.70 ± 0.54	3.06 ± 0.49	NS
g DM d^{-1} sow^{-1}	385 ± 43	935 ± 83	***
Manure-straw ratio	-	3.33 ± 0.44	-
Waste composition			
Dry matter (%)	10.5 ± 1.4	30.8 ± 2.6	***
Organic matter (%)	8.2 ± 1.2	25.7 ± 2.5	***
pH	7.82 ± 0.10	8.53 ± 0.20	**
C/N	8.2 ± 0.8	17.3 ± 2.7	**
Total nitrogen			
g N kg^{-1} waste	5.55 ± 0.38	8.45 ± 1.14	*
g N d^{-1} sow^{-1}	20.39 ± 1.86	25.88 ± 5.59	NS
Ammonium nitrogen			
g NH_4^+-N kg^{-1} waste	2.19 ± 0.18	1.00 ± 0.14	***
g NH_4^+-N d^{-1} sow^{-1}	8.06 ± 1.22	3.08 ± 0.75	***

Significance: NS: $P>0.05$; *: $P<0.05$; **: $P<0.01$; ***: $P<0.001$

3.4. Gas emissions

Table 5 presents the overall means of gas emissions and Figure 2 shows the evolution of the gas emissions from the beginning to the end of stay. Breeding sows on slatted floor rather than on deep litter increased NH_3-emissions by 41% (P<0.001) and CH_4-emissions by 10% (P<0.001), decreased N_2O-emissions by 79% (P<0.001), CO_2eq-emissions by 53% (P<0.001) and CO_2-emissions by 15% (P<0.001), and did not change H_2O-emissions (P>0.05).

Table 5 - Gas emissions as influenced by the floor type - concrete slatted floor (SF) or straw-based deep litter (DL)- in gestating sows (mean ± standard deviation between the 3 batches)

	sow^{-1} day^{-1}	**$place^{-1}$ $year^{-1}$**	**LU^{-1} day^{-1}**	**Significance**
NH_3 (g)				
SF	12.77 ± 1.60	4662 ± 585	30.41 ± 3.81	***
DL	9.05 ± 2.08	3305 ± 758	21.56 ± 4.95	
N_2O (g)				
SF	0.47 ± 0.04	171 ± 15	1.11 ± 0.01	***
DL	2.27 ± 2.15	829 ± 783	5.41 ± 5.11	
CH_4 (g)				
SF	10.12 ± 1.22	3705 ± 445	23.99 ± 2.88	***
DL	9.20 ± 0.98	3358 ± 358	21.89 ± 2.33	
CO_2eq (kg)				
SF	0.44 ± 0.04	161 ± 16	1.05 ± 0.10	***
DL	0.94 ± 0.20	344 ± 73	2.24 ± 0.48	
CO_2 (kg)				
SF	2.41 ± 0.20	880 ± 73	5.70 ± 0.47	***
DL	2.83 ± 0.11	1032 ± 40	6.73 ± 0.26	
H_2O (kg)				
SF	3.25 ± 0.62	1186 ± 226	7.68 ± 1.47	NS
DL	3.21 ± 0.59	1172 ± 215	7.64 ± 1.40	

LU: livestock unit, equal to 500 kg body weight
Significance: NS: $P>0.05$; ***: $P<0.001$

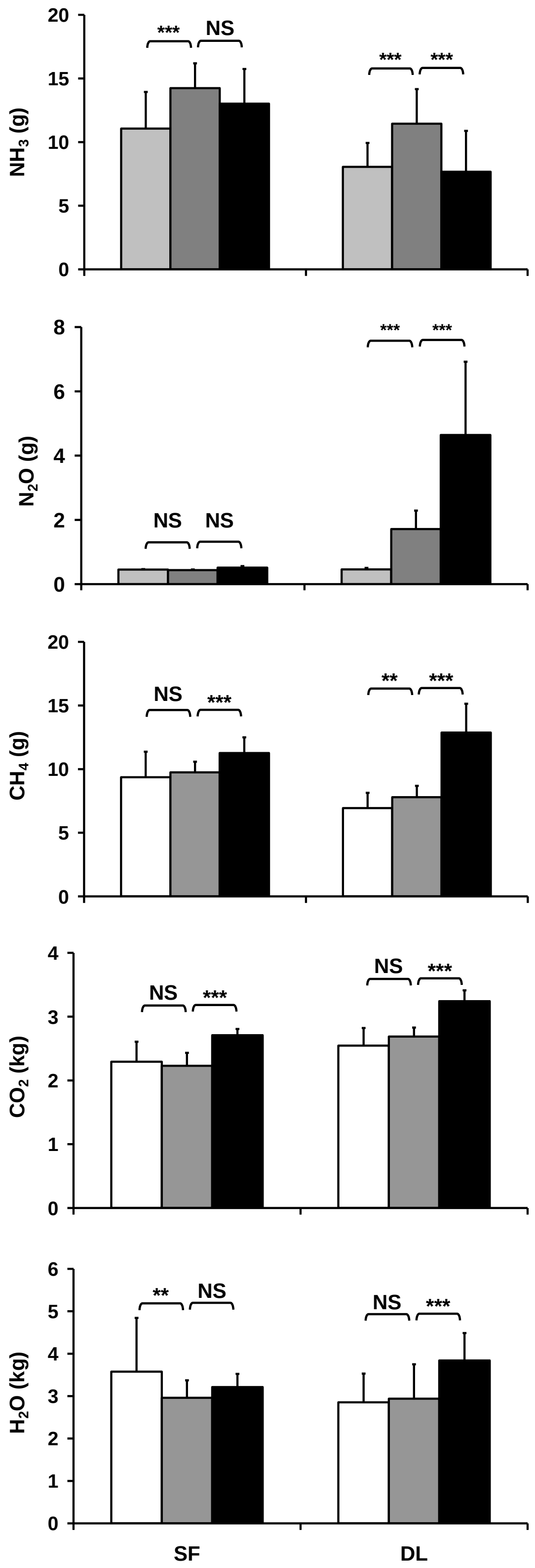

Figure 2 - Gas emissions per day and per sow (mean ± standard deviation between the 3 batches) as influenced by the floor type - concrete slatted floor (SF) or straw-based deep litter (DL)- in gestating sows according to the stay week (white, grey and black bars for weeks 2, 5 and 8 respectively; Significance between week of measurement: NS: $P>0.05$; *: $P<0.05$; **: $P<0.01$; ***: $P<0.001$)

Evolution of NH_3- and H_2O-emissions showed no particular trends throughout time. With slatted floor, N_2O-emissions remained very low and stable during all the stay of sows while with deep litter, N_2O-emissions increased exponentially from week 2 to week 8 of stay. In both groups, CH_4- and CO_2-emissions remained quite stable during the first 2 weeks of measurements and increased during the third week.

3.5. Nitrogen balance

Feed provided 100 % of N-inputs for the SL group and 92% of N-inputs for the DL group, the remaining for this group being supplied by straw (Table 6). A greater N-waste (DL group) was associated to lower NH_3-N-emissions and to greater N_2O-N-emissions. Unaccounted-N amounts to about 25% of outputs in both groups. This can be partly considered as unmeasured dinitrogen (N_2) emissions, especially with the bedded system. The homogenisation and the sampling of the manures can constitute a source of error. The discrepancy between N-inputs and N-outputs can be also attributed to the measurements schedule: NH_3 and N_2O are measured during targeted periods (3 periods of 6 days per batch) while data for N-feed, N-straw and N-waste are representative of the entire housing period.

Table 6 - Nitrogen balance (g N day^{-1} sow^{-1}) as influenced by the floor type - concrete slatted floor (SF) or straw-based deep litter (DL)- in gestating sows (mean ± standard deviation between the 3 batches)

	SF	**DL**	**Significance**
N-inputs			
N-straw	-	4.6 ± 1.0 (8%)	-
N-feed	51.6 ± 0.5 (100%)	52.3 ± 0.9 (92%)	NS
N-retention (estimated)	7.7 ± 0.1 (15%)	7.8 ± 0.1 (15%)	NS
N-outputs			
N-waste	20.5 ± 1.8 (40%)	25.9 ± 5.6 (45%)	NS
NH_3-N	10.5 ± 1.9 (20%)	7.5 ± 2.2 (13%)	NS
N_2O-N	0.3 ± 0.0 (1%)	1.4 ± 0.4 (3%)	**
Unaccounted-N	12.6 ± 3.2 (24%)	14.3 ± 3.1 (25%)	NS

Significance: NS: $P>0.05$; **: $P<0.01$

4. Discussion

NH_3-emissions obtained in this experiment met values presented in the literature ranging from 7 to 30 g NH_3 d^{-1} per sow for group-housed sows kept on litter (Groot Koerkamp *et al.*, 1998; Misselbrook *et al.*, 2000; Dore *et al.*, 2004) or ranging from 6 g to 18 g NH_3 d^{-1} per sow on slatted floor (Groot Koerkamp *et al.*, 1998; Groenestein *et al.*, 2003; Hayes *et al.*, 2006).

In this trial, NH_3-emissions were lower from the DL room than from SL room (-41%). In the literature, comparisons between fully slatted floor and deep litter for fattening pigs or weaned piglets showed conflicting results with greater NH_3-emissions sometimes with slatted floor (Groot Koerkamp *et al.*, 1998; Kermarrec and Robin, 2002; Kavolelis, 2006; Kim *et al.*, 2008) and sometimes with deep litter (Groot Koerkamp *et al.*, 1998; Balsdon *et al.*, 2000; Nicholson *et al.*, 2000; Philippe *et al.*, 2007a; Cabaraux *et al.*, 2009). That can be explained by the wide range of rearing techniques of pigs on litter: the litter type (straw, sawdust, wood chip), the litter management (deep litter, straw flow), the amount of supplied litter and the space allowance. These parameters influence the physical structure (density, humidity) and the chemical properties of the litter and thus the gases emissions level (Dewes, 1996; Groenestein and VanFaassen, 1996; Misselbrook and Powell, 2005).

So, in a former experiment conducted with fattening pigs by Philippe *et al.* (2007a), greater NH_3-emissions were obtained with the deep litter system compared to the slatted floor system, contrary to the current results. The amounts of supplied straw could explain the difference of results. Indeed, while the excreted N was quite similar (around 40 g N d^{-1} per animal) in the 2 experiments, the straw supply was greater with the sows than with the fattening pigs (900 g d^{-1} sow^{-1} *vs.* 400 g d^{-1} pig^{-1}). More straw increased the C/N ratio of the litter what favours the bacterial growth and promotes the N assimilation into stable microbial protein with lower NH_3-emissions as consequence (Dewes, 1996; Sommer and Moller, 2000). This explanation is supported by Gilhespy *et al.* (2009) who observed a reduction of NH_3-emissions with a greater straw supply (8 kg *vs.* 4 kg straw pig^{-1} $week^{-1}$).

In the literature, there are few data on N_2O-emissions associated to gestating sows, especially with bedded systems. For gestating sows kept on slatted floor, emission factors of 0.38 and 1.36 g N_2O d^{-1} sow^{-1} are presented by Dong *et al.* (2007) and Costa and Guarino (2009), respectively. Usually, emission factors presented for fattening pigs kept on slatted floor are relatively low, ranging from 0.11 to 0.67 g N_2O d^{-1} pig^{-1} (Sneath *et al.*, 1997; Osada *et al.*, 1998; Dong *et al.*, 2007; Philippe *et al.*, 2007b; Blanes-Vidal *et al.*, 2008; Costa and Guarino, 2009). Straw-based litter systems are related to greater emissions, around 1 g N_2O d^{-1} pig^{-1} (Robin *et al.*, 1999; Nicks *et al.*, 2004; Philippe *et al.*, 2006). Sawdust-based litters seem to be associated to further great emissions (Groenestein and VanFaassen, 1996; Nicks *et al.*, 2004; Cabaraux *et al.*, 2009). With fattening pigs kept on sawdust litter, Nicks et al., (2004) measured N_2O-emissions around 2 g N_2O d^{-1} pig^{-1}.Experimental comparisons regarding the effect of the floor type shown greater emissions associated to straw-based litter system compared to the slatted floor system as well for weaned piglets (Cabaraux *et al.*, 2009) as for fattening pigs (Philippe *et al.*, 2007a). The current experiment with gestating sows confirmed these results.

The formation of N_2O occurs during incomplete nitrification/denitrification processes that normally convert NH_3 into N_2, a non polluting gas. 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 case of presence of oxygen and/or low availability of degradable carbohydrates (Poth and Focht, 1985; Driemer and Van den Weghe, 1997). N_2O-synthesis needs thus close combination of aerobic and anaerobic areas, heterogeneous conditions met within the litter. These particular conditions explain greater N_2O-emissions usually observed with bedded systems in comparison with slurry systems where the environment is largely anaerobic.

In bedded systems, N_2O-formation may be reduced in case of generous straw supply (Veeken *et al.*, 2002; Basset-Mens *et al.*, 2007) and may be increased by the presence of numerous anaerobic areas (Kaiser and Van den Weghe, 1997). Thus, the increasing N_2O-emissions with the course of time in DL room can be explained by the evolution of the environment inside the litter. Throughout time, dejections are accumulated in the litter with creation of more anaerobic areas close to aerobic areas.

In this experimental design, the removal of the manures and the cleaning of the pens were planned between each batch. In some practical conditions, manures can accumulate in the rooms for a number of batches. In this case, the emission profiles throughout the successive batches could be different than those obtained here. With five successive batches of weaned piglets kept on the same straw litter, Nicks *et al.* (2003) measured regularly increased N_2O-emissions from the first to the third batches and stable emissions around 0.50 g N_2O d^{-1} pig^{-1} thereafter.

Methane originates from anaerobic degradation of organic matter (Hellmann *et al.*, 1997). In piggery, the two main sources are the digestive tract of animal and the waste. The enteric production of CH_4 (g d^{-1}) is function of fibre intakes and could be calculated with the following equation:

$$CH_4 = 7.05\ NSP + 3.05$$

with NSP, the amount of ingested Non Starch Polysaccharides (kg d^{-1}) (Philippe *et al.*, 2008). The CH_4 production from digestive tract could thus be estimated to about 7.5 g d^{-1} sow^{-1} for the two groups because feed intakes were similar. However, in the DL group, the sows ate certainly straw but the ingested amount was not quantifiable. The CH_4 production from digestive tract was thus probably slightly greater with sows from DL group. Nevertheless, total CH_4-emissions were greater from SF room indicating a greater CH_4 production from slurry than from manure in the present trial.

Methanogenesis is mainly performed by mesophilic bacteria (25-40°C) with an optimal pH close to neutrality (El-Mashad *et al.*, 2004). The anaerobic nature and the pH level of slurry favour CH_4 production. In manure, CH_4-release are promoted by high temperature and high DM content (Amon *et al.*, 2006; Haeussermann *et al.*, 2006). Straw supply may enhance CH_4-emissions by increasing the DM-content and degradable carbohydrates content of the manure. On the other hand, straw may inhibit production because of greater manure aeration (Amon *et al.*, 2006; Yamulki, 2006). Thus, as observed for N_2O, more anaerobic conditions with the course of time could explain the increase of CH_4-emissions in the DL room at the third week of measurements. Similarly, experiments conducted on the same straw-based litter during successive batches show increasing CH_4-emissions from one batch to another, as well with weaned piglets (Nicks *et al.*, 2003; Cabaraux *et al.*, 2009) as fattening pigs (Nicks *et al.*, 2004). For example, the mean CH_4 emission per fattening pig and per day was about 4 times higher after 8 months of litter use (Nicks *et al.*, 2004).

The emissions of CO_2eq calculated in this trial were more than two-fold greater with the use of straw litter despite lower NH_3 and CH_4-emissions from this room. This was due to the very high direct N_2O-emission and its great global warming potential. Indeed, in SF room, about 440 g CO_2eq d^{-1} were emitted per sow, coming for 57% from CH_4-emissions, for 32% from direct N_2O-emissions and for 11% from indirect N_2O-emissions. The corresponding values from the DL room were respectively 24%, 72% and 4% with total CO_2eq-emissions of 940 g d^{-1} sow^{-1}.

The CO_2 production from piggeries originates mainly from the animal respiration but also from the waste releases. CO_2-exhalation by pigs is function of energy metabolism and thus of body weight, feed intakes and animal activity (CIGR, 2002; Pedersen *et al.*, 2008). In the present trial, the two groups had the same body weight and feed intakes. CO_2-emissions released from waste must not be neglected. CO_2-production in waste has two origins: the hydrolysis of urea leading to NH_3- and CO_2-production, and the anaerobic degradation of organic components which is the most important origin (Ni *et al.*, 1999). It is generally admitted that emissions are greater from litter than from slurry (Philippe *et al.*, 2007a; Pedersen *et al.*, 2008; Cabaraux *et al.*, 2009). Inside the litter, the production is influenced by temperature, moisture content, C/N ratio, pH level, oxygen level and the physical structure of the organic material (Jeppsson, 2000). The greater CO_2-emissions observed at the end of the experiment could be explained by the greater metabolism of the sows at the end of the gestation and the accumulation of manure in the course of time (and thus the more anaerobic conditions met within the litter). In the literature, when successive batches of animals are raised on the same litter, no particular trends are observed from one batch to another (Nicks *et al.*, 2003; Nicks *et al.*, 2004; Cabaraux *et al.*, 2009). However, within the same batch, emissions regularly increase in the course of time, as obtained in the present trial.

Like CH_4 and CO_2, H_2O-emissions have two origins: animals and waste. Evaporation by animals is function of body weight, heat production and ambient temperature (CIGR, 2002). Evaporation from slurry is often considered as negligible (de Oliveira *et al.*, 1998; Philippe *et al.*, 2007a) while evaporation from manure is more important and function of litter temperature related to the level of the microbial fermentations. However, in the current experiment, there was no significant difference about H_2O-emissions between the 2 groups. In SF room, the greater H_2O-emissions observed at the beginning of the trial could be due to the added water in the slurry pit and, in DL room, the greater H_2O-emissions observed at the end of the trial could be due to the usual increase of the litter temperature with the time.

5. Conclusion

Rearing sows on straw deep litter is known to support the animal welfare and to have a good brand image for the consumer. In the present trial, the reproductive performance was not modified compared to the slatted floor system. However, the environmental impact of the bedded system seems to show conflicting results. Indeed, the main disadvantage of the deep litter system was the greater N_2O-emissions and thus, the greater CO_2eq-emissions. On the other hand, this floor type was related to reduced NH_3- and CH_4-emissions. The choice in favour of a floor type will depend on the relative importance given to the different parameters as welfare, cost management, ammonia and greenhouse emissions.

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3. Effets de la surface disponible sur les emissions gazeuses associees a l'elevage en groupe de truies gestantes sur litiere de paille accumulee

Lors des deux études précédentes, des résultats discordants ont été observés quant aux effets du type de sol, caillebotis ou litière paillée, sur les émissions de NH_3. Lors de la première étude menée avec des porcs charcutiers, des émissions plus élevées de NH_3 avaient été observées avec le logement sur litière de paille accumulée. A l'inverse, la deuxième étude menée avec des truies gestantes avait abouti à des émissions plus élevées associées au sol à caillebotis. Une des hypothèses émises pour expliquer ces résultats opposés était la différence de surface disponible par animal. En effet, les porcs charcutiers élevés sur paille disposaient d'une surface 58% plus grande que ceux logés sur caillebotis (1,20 *versus* 0,76 m^2 par porc) alors que pour les truies gestantes la densité animale était identique pour les deux modes d'hébergement (2,5 m^2 par truie). Plusieurs études ont montré qu'une augmentation de l'espace disponible améliorait le bien-être des truies en groupe (Salak-Johnson *et al.*, 2007; Remience et al., 2008). Par contre, peu de recherches ont porté sur l'impact de la densité animale sur les émissions de gaz polluants, spécialement pour les logements avec litière. Cette étude a donc pour objectif d'évaluer l'effet d'une augmentation de l'espace disponible sur les émissions de NH_3, N_2O, CH_4 et CO_2 lors de l'hébergement de truies gestantes sur litière de paille accumulée.

Deux locaux identiques en volume (103 m^3) et en surface (30 m^2) ont été équipés d'une loge permettant d'héberger un groupe de 5 truies gestantes. Les loges étaient composées d'une zone d'alimentation, constituée de 5 cages individuelles (1,2 m^2/truie) disposées sur un sol bétonné et dont l'accès était limité aux périodes de repas (1 repas d'une heure par jour), et d'une zone de repos consistant en une litière de paille accumulée d'une surface de 12,6 m^2 (2,5 m^2/truie) dans une loge et de 15,1 m^2 (3,0 m^2/truie) dans l'autre loge. Avant l'arrivée des animaux, 150 kg de paille de blé entière ont été disposés dans les loges afin de former la couche initiale de litière d'une épaisseur de 25-30 cm. A intervalles d'environ deux semaines, des apports supplémentaires de paille ont été réalisés simultanément et en quantités identiques dans les deux locaux pour atteindre en fin de gestation un paillage équivalent à 1,33 kg $truie^{-1}$ $jour^{-1}$ dans les deux locaux.

Quatre bandes successives de 10 truies gestantes de race Landrace belge, réparties uniformément en deux groupes en fonction de la parité, du poids et de l'épaisseur de lard dorsal, ont été hébergées dans les locaux depuis la 6ème semaine de gestation jusqu'à 7 jours avant la date prévue de mise-bas, soit environ 10 semaines. Après le départ de chaque bande de truies, les effluents (lisiers et fumiers) étaient évacués et les loges étaient nettoyées. La ventilation des locaux se faisait au moyen de ventilateurs extracteurs (un par loge) et de manière contrôlée avec adaptation automatique du débit de ventilation en fonction de la température, ces deux paramètres étant mesurés et enregistrés en continu (Fancom, Panningen, Pays-Bas). Les concentrations en gaz ont été mesurées dans les locaux expérimentaux et dans le couloir d'apport d'air par détection photo-acoustique infrarouge au moyen d'un moniteur équipé pour la mesure simultanée de NH_3, N_2O, CH_4, CO_2 et H_2O (1412 Photoacoustic Multi-Gas Monitor, Innova Air Tech Instruments, Nærum, Denmark). Trois séries de mesures de six jours consécutifs réparties de manière homogène sur la période de gestation ont été réalisées pour chaque bande de truies. Les émissions (E_{gaz}) ont été calculées sur base horaire grâce à l'équation suivante :

$E_{gaz} = D \times (C_i - C_e)$,

avec D, le débit de ventilation (kg air h^{-1}), et C_i et C_e, respectivement la concentration en gaz dans l'air du local expérimental et du couloir d'apport d'air (mg kg^{-1} air). Les résultats d'émissions ont été testés au moyen d'un modèle mixte pour données répétées (SAS, Mixed Proc) en incluant l'effet du type de surface (1 dl), de la série de mesure (2 dl) et de l'interaction surface-série (2 dl) avec 144 données (24 heures x 6 jours) par série de mesure.

En accroissant la surface disponible de 20%, les émissions de NH_3 ont été augmentées de 17% (7,64 *versus* 6,52 g NH_3 truie^{-1} jour^{-1}, $P<0,01$). Cela confirme l'hypothèse selon laquelle la production de NH_3 est directement proportionnelle à la surface d'émission (Monteny et Erisman, 1998). En engraissement sur sols à caillebotis, Guingand (2007) avait observé des émissions plus élevées de 35% alors que l'espace disponible avait augmenté de 43%. A l'opposé, Basset-Mens et al. (2007) ont rapporté des émissions doublées alors que la surface paillée était réduite de moitié. Ils s'expliquaient ce résultat par des températures ambiantes et des ventilations plus élevées liées à la plus grande densité animale. Dans la présente étude, les conditions d'ambiance étaient similaires dans les deux locaux expérimentaux.

Les émissions de N_2O les plus basses ont été mesurées avec la densité animale la moins élevée (2,80 *versus* 3,90 g N_2O truie^{-1} jour^{-1}, $P<0,01$), ce qui rejoint les résultats de Hassouna et al. (2005) obtenus avec des porcs charcutiers sur litière. En augmentant l'espace disponible, on accroit la surface de litière directement en contact avec l'air et on limite le tassement de celle-ci par les animaux. Or, au sein des fumiers, des conditions davantage aérobies sont connues pour réduire les émissions de N_2O (Kermarrec et Robin, 2002).

Les émissions de CH_4 ont également été réduites avec la plus grande surface paillée (10,15 *versus* 15,21 g CH_4 truie^{-1} jour^{-1}, $P<0,001$). La production entérique, qui tient compte de la composition en fibres de l'aliment, peut être estimée à 8,5 g truie^{-1} jour^{-1}, pour les deux groupes d'animaux (Philippe et al., 2008). La différence d'émission au niveau des loges proviendrait donc de la production de CH_4 par les fumiers. Le caractère plus aéré de la litière lié à la plus grande surface disponible peut expliquer la réduction du taux de méthanogenèse, processus strictement anaérobie (Yamulki, 2006).

Les émissions de CO_2 ont été diminuées lorsque l'espace disponible a été porté à 3,0 m^2 par truie (2,12 *versus* 2,41 kg CO_2 truie^{-1} jour^{-1}, P<0,001). La respiration des animaux, qui est la source principale de CO_2 et qui est fonction du métabolisme, est estimée identique pour les deux densités animales testées. Les caractéristiques physico-chimiques des litières seraient donc à l'origine de la différence d'émissions observée. En effet, le processus de compostage, responsable majoritaire de la production de CO_2 par les fumiers, est dépendant de nombreux facteurs qui interagissent entre eux tels la température, la teneur en humidité, le rapport C/N, la dégradabilité de la matière organique, le pH et la structure physique de l'effluent (Andersson, 1996; Jeppsson, 2000; Paillat et al., 2005). Les conditions favorables à sa formation semblent donc davantage avoir été rencontrées au sein des litières associées à la plus grande densité animale.

En conclusion, augmenter l'espace disponible de 2,5 à 3,0 m^2 par truie élevée en groupe sur litière de paille accumulée a induit une augmentation des émissions de NH_3, probablement due à une plus grande surface d'émissions. Ce résultat conforte l'hypothèse proposée pour expliquer la différence observée entre porcs charcutiers et truies gestante quant à l'effet du type de sol, litière ou caillebotis, sur les émissions de NH_3. D'autre part, une réduction des émissions de GES (N_2O, CH_4 et CO_2) a été observée avec la plus faible densité animale, en raison de modifications engendrées dans les propriétés physico-chimique des fumiers.

Effects of available surface on gaseous emissions from group-housed gestating sows kept on deep litter

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Keywords

Ammonia - Available surface - Deep litter - Gestating sow - Greenhouse gases

Abstract

In the European Union, the group-housed pregnant sows have to have a minimal legal available area of 2.25 m^2/sow. However, it has been observed that an increased space allowance reduces agonistic behaviour and consecutive wounds and thus induces better welfare conditions. But, what about the environmental impacts of this greater available area? Therefore, the aim of this study was to quantify pollutant gas emissions (nitrous oxide -N_2O-, methane -CH_4-, carbon dioxide -CO_2- and ammonia -NH_3-), according to the space allowance in the raising of gestating sows group-housed on a straw-based deep litter. Four successive batches of 10 gestating sows were each divided into two homogeneous groups and randomly allocated to a treatment: 2.5 vs. 3.0 m^2/sow. The groups were separately kept in two identical rooms. A restricted conventional cereals based diet was provided once a day in individual feeding stalls available only during the feeding time. Rooms were automatically ventilated. The gas emissions were measured by infra red photoacoustic detection during six consecutive days at the 6th, 9th and 12th weeks of gestation. Sows performance (body weight gain, backfat thickness, number and weight of piglets) was not significantly different according to the space allowance. In the room with 3.0 m^2/sow and compared to the room with 2.5 m^2/sow, gaseous emissions

were significantly greater for NH_3 (6.29 vs. 5.37 g NH_3-N/d per sow; $P<0.01$) and significantly lower for N_2O (1.78 vs. 2.48 g N_2O-N/d per sow; $P<0.01$), CH_4 (10.15 vs. 15.21 g/d per sow; $P<0.001$), CO_2 equivalents (1.11 vs. 1.55 kg/d per sow; $P<0.001$), CO_2 (2.12 vs. 2.41 kg/d per sow; $P<0.001$) and H_2O (3.10 vs. 3.68 kg/d per sow; $P<0.001$). In conclusion, an increase of the available area for group-housed gestating sow kept on straw based deep litter seems to be ambiguous on an environmental impacts point of view. Compared with a conventional and legal available area, it favoured NH_3 emissions, probably due to an increased emitting surface. However, about greenhouse gases, it decreased N_2O, CH_4 and CO_2 emissions, probably due to reduced anaerobic conditions required for their synthesis, and led to a reduction of CO_2 equivalents emissions.

Implications

On one hand, there are currently many experiments carried out in order to assess and improve livestock welfare and, indirectly, to give a better brand image of agriculture to consumers. On the other hand, environmental effects of agriculture are more and more considered, especially its impact on global warming. Without forgetting economic profitability, farmers have to compromise between all these aspects. The goal of this trial was thus to bring some scientific elements in this debate. So, we observed an increase of ammonia emissions and a decrease of greenhouse gases emissions related to greater space allowance for gestating sows group-housed on deep litter.

1. Introduction

By 2013, the use of individual gestation accommodations for dry sows will be banned in the European Union (directive 2001/88/CE) and sows will have to be kept in groups at least from 4 weeks after insemination till 1 week before farrowing. This directive fixes also the minimal legal space allowance to 2.25 m^2/sow and 1.64 m^2/gilt, plus or minus 10% if the pigs number in the group is lower than six animals or upper than 40 animals respectively. Behavioural impact of an increased space allowance has been quite largely studied with gestating sows, concluding in improved welfare with lower animal density (Salak-Johnson *et al.*, 2007; Remience *et al.*, 2008). However, effects of space allowance on environmental parameters, such as gaseous emissions, have been slightly studied, especially with pigs kept on litter.

Ammonia (NH_3) emissions contribute to soil and water acidification and eutrophication and to indirect emissions of nitrous oxide (N_2O) (IPCC, 2006). Furthermore, NH_3 is well known as a toxic gas, irritating the respiratory tract at concentrations exceeding 15 ppm (Banhazi *et al.*, 2008). In Europe, approximately 80% of NH_3 production originated from animal production facilities (Reidy *et al.*, 2009).

The greenhouse gases (GHG) associated with livestock production are N_2O, methane (CH_4) and carbon dioxide (CO_2). These gases take part to the global warming and climate change issues. The global warming potential (GWP) of a specific gas evaluates its contribution on the global warming. It depends on its absorption of infrared radiation, the spectral location of its absorbing wavelengths and on its atmospheric lifetime. Commonly, a time horizon of 100 years is used as regards to average lifetime of GHG. N_2O and CH_4 are important contributors because their GWP over a 100-year period are 21 and 310 times that of CO_2 respectively (IPCC, 2007). N_2O also contributes to the destruction of the ozone shield. The case of CO_2 is specific because it is usually estimated that CO_2 production by livestock is compensated by CO_2 consumption by photosynthesis of plants used as feed. Therefore, according to IPCC guidelines (IPCC, 2006), CO_2 emissions from livestock are not estimated. However, experiments carried out with weaning and fattening pigs (Philippe *et al.*, 2007a and 2007b; Cabaraux *et al.*, 2009) showed that CO_2-emissions might differ in relation to housing conditions while diet characteristics, feed intakes, animal performances and climate conditions were similar. The study of CO_2-production from livestock buildings is also important because reference emissions factors are needed for ventilation rate estimation by mass balance method that is particularly used for naturally ventilated buildings (Pedersen *et al.*, 2008).

Moisture balance can also be used for ventilation rate estimation (Blanes et Pedersen, 2005). Besides, humidity has significant influence on airborne pollutants in piggeries, like respirable particles and endotoxins (Banhazi *et al.*, 2008). Bedded systems are known to release more moisture than conventional systems (CIGR, 2002; Philippe *et al.*, 2007a) with likely excessive indoor relative humidity and poor air quality as consequence, especially during wintertime. Thus, determination of water vapour (H_2O) emissions is a key factor in specifying ventilation rates in livestock buildings.

Usually, national inventories of pollutant gasses are based on default values obtained by estimation for different animal categories (IPCC, 2006; Reidy *et al.*,2009). A part of uncertainty comes from a lack of data for all the animal and housing conditions (Reidy el al., 2009). Nowadays, there are few data about gaseous emissions from pigs on deep litter and still less with gestating sows in an increased available space. In France, from 10% to 15% of gestating sows are kept on bedded systems (Massabie and Ramonet, 2007). Therefore, the aim of this study was to quantify gaseous emissions (NH_3, N_2O, CH_4, CO_2 and H_2O) in the raising of gestating sows group-housed on a straw-based deep litter according to the space allowance (2.5 vs. 3.0 m^2sow).

2. Materials and methods

The trials were carried out in experimental rooms located at the Faculty of Veterinary Medicine of Liège University (Belgium). The ethical committee of the University of Liège approved the use and treatment of animals in this study.

Experimental rooms

Two experimental rooms, similar in volume (103 m^3) and surface (30.2 m^2), were arranged and equipped for this experiment. Rooms consisted of a service area and a pen to house a group of five gestating sows. Pens were divided in a straw-bedded area and five individual feeding stalls (figure 1). The feeding stalls were raised the height of 30 cm and were equipped with front troughs and rear gates preventing the access to the stalls outside of the feeding time. The surface of bedded area was 12.6 m^2 (2.5 m^2 per sow) in room 1 and 15.1 m^2 (3.0 m^2 per sow) in room 2. In each pen, before the arrival of the animals, about 150 kg of whole wheat straw were used to constitute the initial deep litter of about 25-30 cm depth. Thereafter, weighted supplementary amounts of straw were provided regularly depending on the cleanliness of the litter and the sows. Whithin each batch, the successive straw supplies were similar in weight in the two pens and occurred at the same time with an interval of about 2 weeks. Between each batch, the pens were cleaned. The manures were weighted and sampled, and their dry matter (DM), organic matter and nitrogen-contents, analysed by the Kjeldahl method, were determined.

Room A2.5

with an available surface of 2.5 m² per gestating sow

Room A3.0

with an available surface of 3.0 m² per gestating sow

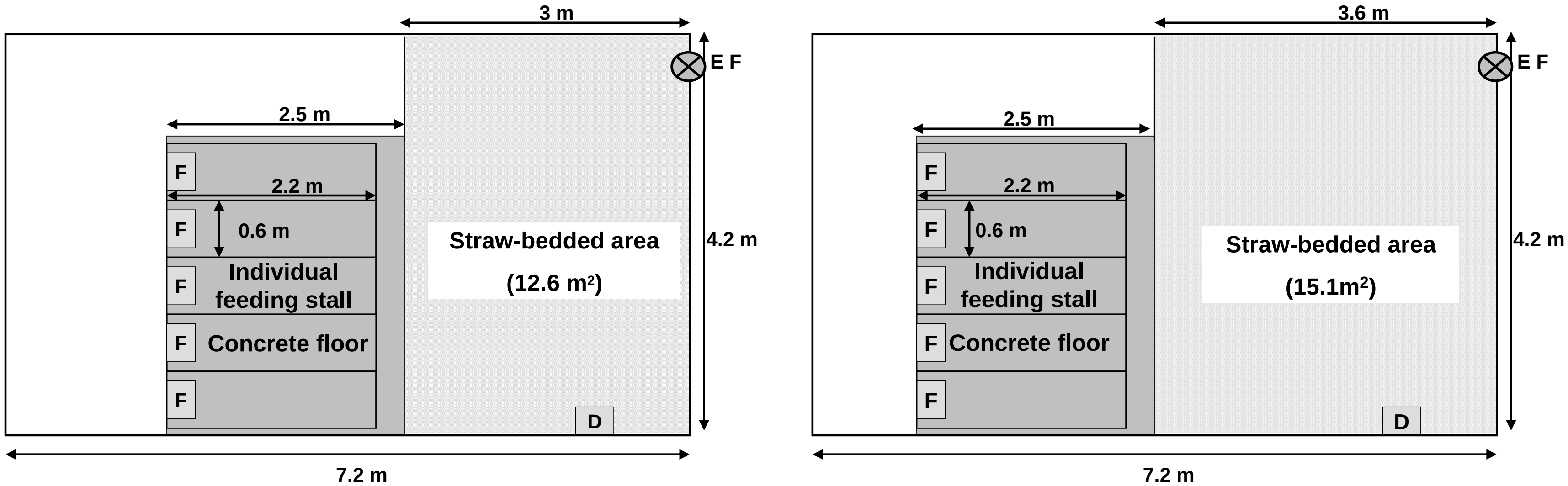

Figure 1 - Plan of the experimental rooms (F: feeding trough; D: drinker; EF: exhaust fan)

Each room was ventilated with an exhaust fan (Fancom, Panningen, The Netherlands) and the ventilation rate was adapted automatically to maintain a constant ambient temperature by means of regulator FCTA (Fancom, Panningen, The Netherlands). Fresh air entered through an opening of 0.34 m^2 which was connected to the service corridor of the building; the outside air was thereby preheated before entering the experimental rooms. The air temperatures of the experimental rooms, the corridor and the outside were measured automatically every hour. The ventilation rates were measured continuously and the hourly means were recorded with an Exavent apparatus (Fancom, Panningen, The Netherlands) with accuracy of 35 m^3/h, i.e. 1% of the maximum ventilation rate of the fan.

Animals and feed

Four successive batches of 10 Belgian Landrace gestating sows were used. They were divided into two homogeneous groups of five animals according to the parity, the body weight and the backfat thickness. Each group was randomly allocated to a treatment: 2.5m^2 (A2.5) or 3.0m^2 (A3.0) available area per sow. Four weeks after service, the sows arrived in the experimental rooms and 15 days prior to giving birth, they moved to farrowing pens; the stay duration was thus 10 weeks for each batch.

The sows received a commercial conventional gestation diet based on cereals (66% of wheat, wheat bran, barley and corn; 2120 kcal net energy/kg, 13.2% CP, 18% NDF). The amounts of daily feed were restricted and determined per batch as function of parity and backfat thickness. The feed was supplied once a day at 0830 h and the sows were blocked in individual feeding stalls during the feeding time (1 h). There was a drinker with *ad libitum* access in each pen.

Individually, the sows were weighted and the backfat thickness was measured on P2-site by ultrasonography at the beginning and at the end of the trial period. The feed and water intakes were recorded per group and per batch. Moreover, at birth, the number of piglets born alive and stillborn was also recorded.

Gas emissions measurement

The concentrations of gases in the experimental rooms and in the corridor supplying fresh air were measured by infrared photoacoustic detection with a Photoacoustic Multi-gas Monitor - INNOVA 1312 (LumaSense Technologies A/S, Ballerup, Denmark) equipped and calibrated for simultaneous measurement of NH_3, N_2O, CH_4, CO_2 and H_2O.

The lower levels of detection were 0.2 ppm for NH_3, 0.03 ppm for N_2O, 0.1 ppm for CH_4 and 3.4 ppm for CO_2, with an accuracy rate of 95%. The air in the experimental rooms was sampled just upstream of the exhaust fan and that one of the corridor, at 1 m from the air inlet. For each batch, the concentrations were measured during three periods of six consecutive days (weeks 6, 9 and 12 of gestation). The Multi-gas monitor was programmed by conducting a cycle of three measurements every hour, once every 20 min, the air being sampled successively in the two experimental rooms and the corridor.
For each gas, the emissions (E_{gas}) were calculated on an hourly basis and expressed in mg/h using the following formula:

$$E_{gas} = D \times (C_{in} - C_{out})$$

with D, the hourly mass flow (kg air/h); C_{in} and C_{out}, the concentrations of gas in the air of the experimental room and corridor respectively (mg/kg air).The mean emissions per day and per sow were calculated for each series of measurements.
For assessment of GHG, they were expressed in CO_2 equivalents (CO_2eq) taking into account their GWP warming potentials. As early mentionned, CO_2 emissions from livestock were excluded from this estimation. But indirect emissions of N_2O were incorporated in this estimation according to IPCC guidelines (IPCC, 2006). Indirect N_2O originate from atmospheric deposition of NH_3 on soils and water surfaces and were estimated considering conversion of 1% of NH_3-N into N_2O-N. Thus, the emissions of CO_2eq were calculated using the following equation:

$$E_{CO2eq} = 21\ E_{CH4} + 310\ x\ (E_{N2O} + 0.01\ x\ NH_3\text{-}N\ x\ 44/28)$$

Nitrogen balance

Nitrogen (N) balance (g N/day per sow) was calculated for each group with inputs corresponding to N-straw and N-feed intakes and outputs corresponding to N-retention by sows, N-content of manure and N from gaseous emissions of NH_3, N_2O and dinitrogen (N_2). Straw protein content was estimated to 38.6 g/kg (Sauvant *et al.*, 2004). N-retention was calculated as a part of N-feed. According to Philippe *et al.* (2008), N-retention coefficient is similar despite different fibrous content and estimated at 15%. Nitrogen from N_2 was calculated by the following equation:

$$N_2\text{-}N = (N\text{-}straw + N\text{-}feed) - (N\text{-}retained + N\text{-}manure + NH_3\text{-}N + N_2O\text{-}N).$$

Statistical analyses

For performance data recorded per sow, the differences between groups housed on two different areas (A2.5 vs. A3.0) were tested using analysis of variance with two criteria (proc GLM) (SAS, 2005): area (1 df), batches (3 df) and interaction between area and batches. For intakes data, manure characteristics and N balance, recorded per pen, the differences were tested in the same way but with only area (1 df) as criterion (proc GLM) (SAS, 2005).

For room temperatures, ventilation rates, gas concentrations and gas emissions, the data from each batch were tested in the form of a mixed model for repeated measurements with two criteria (proc MIXED) (SAS, 2005): area (1 df) and week of measurement (2 df), with 144 (24 h X 6 days) successive measurements per week. The combined data from the four batches were tested in the same way but including interaction between area and week of measurement (2 df).Residuals were normally distributed, with a null expectation (proc UNIVARIATE) (SAS, 2005). Correlation between successive measurements was modelled using a type 1-autoregressive structure.

3. Results

Climatic characteristics of the rooms

The data about the air temperatures and the ventilation rates are shown in Table 1. The average temperatures of the air were similar in both experimental rooms with about 18.5 °C ($P>0.05$), 16.6 °C in the service corridor and 11.6 °C outside. The lower temperatures in experimental rooms during the second batch were due to cooler temperature of the outside and incoming air. Nevertheless, despite large variations of the outside temperatures between batches, the temperatures in the experimental rooms stayed stable with a standard deviation between batches around 2 °C. This was due to the automatic adaptation of the ventilation rates to the inside temperatures. The mean ventilation rate was about 250 m^3/h per sow, without significant difference between groups ($P>0.05$). This quite high flow was explained by the preheating of the air in the service corridor. On hourly basis and per sow, the extreme values of ventilation rates were 157 m^3 and 513 m^3 for the room A2.5, and 129 m^3 and 479 m^3 for the room A3.0.The slightly higher ventilation rates in the room A2.5 were explained by the thermal leakage of the walls being lower in room A2.5, linked to the positioning of these rooms in the building.

Table 1 - Air temperatures and ventilation rates of experimental rooms, service corridor and outside

	Batches				
	1[a]	**2**[a]	**3**[a]	**4**[a]	**1 to 4**[b]
Temperatures (°C)					
Room A2.5	20.7 ± 1.1	16.3 ± 1.7	18.0 ± 3.1	19.4 ± 1.1	18.6 ± 1.9
Room A3.0	20.7 ± 0.9	16.3 ± 1.6	18.0 ± 2.8	18.9 ± 0.7	18.5 ± 1.8
Service corridor	18.5 ± 1.6	14.1 ± 2.3	16.4 ± 3.6	17.3 ± 1.3	16.6 ± 1.9
Outside	12.9 ± 4.9	4.0 ± 4.0	13.4 ± 5.4	16.0 ± 1.4	11.6 ± 5.2
Ventilation rates (m^3/h per sow)					
Room A2.5	298 ± 41	166 ± 90	229 ± 76	360 ± 79	263 ± 84
Room A3.0	271 ± 30	174 ± 25	213 ± 89	300 ± 67	240 ± 57

Room A2.5: room with an available area of 2.5m^2 per gestating sow; Room A3.0: room with an available area of 3.0m^2 per gestating sow

[a] Mean ± standard deviation between mean values of the 3 periods of measurements

[b] Mean ± standard deviation between the 4 batches

Animal performance

The average staying duration of batches was 70 ± 5 days. The performance is presented in Table 2. There were no significant differences between groups according to the available surface for animal performance. The mean initial and final body weights were 205 kg and 259 kg respectively with an average daily gain of 723 g/d and an average feed intake of 2.99 kg/d. The mean initial and final backfat thicknesses were 14.9 mm and 21.1 mm respectively with a backfat thickness gain of 6.2 mm. On average, each sow gave birth to 11.9 piglets of which 10.5 were alive.

Amounts and composition of manure

Characteristics of manure did not significantly differ between groups (P>0.05) (Table 3). The amounts of supplied straw and collected manure were per sow about 1.3 kg/d and 3.9 kg/d. The DM and organic matter contents and the pH of the manure were 29%, 25% and 8.27 respectively. Nitrogen and ammonium contents were 8.27 g N and 1.65 g N-NH_4^+ per kg fresh manure respectively.

Table 2 - Animal performance as influenced by the available area (2.5 m^2 (Room A2.5) or 3.0 m^2 (Room A3.0) per sow) in group-housed gestating sows kept on deep litter (mean ± standard deviation between the 4 batches)

	Room A2.5	**Room A3.0**
Number of sows	20	20
Parity	4.4 ± 1.3	4.6 ± 1.4
Initial body weight (kg)	202.9 ± 5.3	206.2 ± 7.8
Final body weight (kg)	255.4 ± 8.0	263.2 ± 10.3
Body weight gain (kg)	52.5 ± 8.6	53.4 ± 9.9
Average daily gain (g/d)	719.5 ± 160.0	727.3 ± 150.1
Feed intake (kg/d)	2.99 ± 0.26	2.99 ± 0.22
Water intake (l/d)	7.6 ± 1.9	7.0 ± 0.3
Initial backfat thickness (mm)	14.5 ± 2.4	15.2 ± 1.8
Final backfat thickness (mm)	20.7 ± 2.2	21.5 ± 3.1
Backfat thickness gain (mm)	6.2 ± 2.0	6.2 ± 2.0
Number of born piglets		
Alive	11.0 ± 1.1	10.0 ± 1.1
Stillborn	1.8 ± 1.2	1.1 ± 1.0
Total	12.7 ± 0.9	11.1 ± 1.5

Table 3 - Manure characteristics as influenced by the available area (2.5 m^2 (Room A2.5) or 3.0 m^2 (Room A3.0) per sow) in group-housed gestating sows kept on deep litter (mean ± standard deviation between the 4 batches)

	Room A2.5	**Room A3.0**
Supplied straw (kg/d per sow)	1.33 ± 0.22	1.33 ± 0.22
Collected manure (kg/d per sow)	3.93 ± 0.96	3.88 ± 0.42
Manure-straw ratio	2.93 ± 0.50	2.94 ± 0.30
Manure composition		
Dry matter (%)	28.8 ± 5.0	29.4 ± 4.3
Organic matter (%)	24.1 ± 4.4	25.2 ± 3.5
pH	8.24 ± 0.13	8.30 ± 0.18
Total nitrogen		
g N/kg manure	8.49 ± 1.36	8.05 ± 2.29
g N/d per sow	32.44 ± 4.88	31.90 ± 12.10
Ammonia nitrogen		
g N-NH_4^+/kg manure	1.73 ± 0.80	1.56 ± 0.88
g N-NH_4^+/d per sow	6.46 ± 2.90	6.21 ± 4.07

Gas concentrations and emissions

In the service corridor providing fresh air, the mean gas concentrations were 2.68 ± 0.71 ppm for NH_3, 0.43 ± 0.05 ppm for N_2O, 5.77 ± 1.67 ppm for CH_4, 476.4 ± 33.9 ppm for CO_2 and 9.13 ± 1.98 g/m^3 for H_2O (mean ± standard deviation between the 4 batches). Table 4 presents the mean gas concentrations in the two experimental rooms. Increased space allowance from 2.5 to 3.0 m^2 raised the concentrations of NH_3 but decreased the concentrations of N_2O, CH_4, CO_2 and H_2O. The difference were not statistically significant, excepted for CH_4 ($P<0.01$). Table 5 presents the mean gas emissions. With the lower animal density, there is an increase of NH_3 emissions by 17% ($P<0.01$) but a decrease of N_2O emissions by 28% ($P<0.01$), CH_4 emissions by 33% ($P<0.001$), CO_2eq emissions by 28% ($P<0.001$), CO_2 emissions by 12% ($P<0.001$) and H_2O emissions by 16% ($P<0.001$).

Figure 2 shows the evolution of the gas emissions from the first period of measurement (6th week of gestation) to the last period of measurement (12th week of gestation). Evolution of NH_3 emissions shows no particular trends throughout time. N_2O-emissions are relatively low at the beginning of the experiment with about 0.50 g N_2O-N/d per sow for both groups. With the space area of 2.5 m^2, emission level reaches about 3.40 g N_2O-N/d per sow from the second measurements period and remains quite stable thereafter. With the space area of 3.0 m^2, emission levels raises regularly throughout time with an intermediate value of 1.64 g N_2O-N/d per sow for the 9th week and an upper value of 3.40 g N_2O-N/d per sow for the 12th week of gestation. CH_4-emissions increase steadily with the course of time in the two groups. While there is no significant difference between groups for the two first periods of measurement ($P>0.05$), the difference becomes highly significant for the 12th week of gestation with twofold CH_4-emissions for the high animal density (28.1 *versus* 15.3 g CH_4/d per sow, $P<0.001$). The evolution of CO_2- and H_2O-emissions is similar for the two groups: the emission levels are stable during the two first periods of measurement and increase at the end of the experiment. However, for these two gasses, differences between groups are always significant within each period of measurement ($P<0.05$).

Table 4 - Gas concentrations for group-housed gestating sows kept on deep litter with an available surface per sow of 2.5 m² (Room A2.5) or 3.0 m² (Room A3.0)

	Room A2.5	Room A3.0	Significance
Batch 1[a]			
NH_3 (ppm)	4.41 ± 0.44	4.51 ± 0.39	NS
N_2O (ppm)	0.65 ± 0.15	0.68 ± 0.20	NS
CH_4 (ppm)	12.42 ± 3.73	10.72 ± 1.95	NS
CO_2 (ppm)	646.6 ± 64.1	621.5 ± 63.4	NS
H_2O (g/m³)	10.51 ± 2.00	10.46 ± 1.99	NS
Batch 2[a]			
NH_3 (ppm)	5.42 ± 0.42	6.08 ± 1.23	NS
N_2O (ppm)	1.33 ± 0.66	0.95 ± 0.58	*
CH_4 (ppm)	8.54 ± 2.00	7.29 ± 0.84	NS
CO_2 (ppm)	808.9 ± 53.5	753.2 ± 62.5	NS
H_2O (g/m³)	7.50 ± 1.51	7.36 ± 1.45	NS
Batch 3[a]			
NH_3 (ppm)	4.95 ± 1.79	5.76 ± 1.92	NS
N_2O (ppm)	0.79 ± 0.05	0.56 ± 0.07	**
CH_4 (ppm)	11.68 ± 6.41	8.75 ± 3.09	*
CO_2 (ppm)	751.5 ± 116.9	771.1 ± 144.7	NS
H_2O (g/m³)	9.29 ± 1.81	9.21 ± 1.77	NS
Batch 4[a]			
NH_3 (ppm)	2.58 ± 0.47	2.93 ± 0.71	NS
N_2O (ppm)	0.54 ± 0.16	0.62 ± 0.20	NS
CH_4 (ppm)	6.64 ± 0.13	7.53 ± 0.57	*
CO_2 (ppm)	615.2 ± 30.5	636.6 ± 49.2	NS
H_2O (g/m³)	11.77 ± 0.91	11.82 ± 0.86	NS
Batch 1 to 4[b]			
NH_3 (ppm)	4.34 ± 1.24	4.82 ± 1.43	NS
N_2O (ppm)	0.83 ± 0.35	0.70 ± 0.17	NS
CH_4 (ppm)	9.82 ± 2.70	8.57 ± 1.57	**
CO_2 (ppm)	705.5 ± 90.2	695.6 ± 77.4	NS
H_2O (g/m³)	9.77 ± 1.82	9.71 ± 1.89	NS

***: P<0.001; **: P<0.01; *: P<0.05; NS: not significant
[a]: For each gas and each available surface, means ± standard deviation between the three periods of measurement
[b]: For each gas and each available surface, means ± standard deviation between the four batches

Table 5 - Gas emissions from group-housed gestating sows kept on deep litter with an available surface per sow of 2.5 m^2 (Room A2.5) or 3.0 m^2 (Room A3.0)

	Room A2.5	Room A3.0	Significance
Batch 1[a]			
NH_3 (g N)	5.96 ± 0.75	5.85 ± 1.21	NS
N_2O (g N)	1.54 ± 0.80	1.61 ± 1.07	NS
CH_4 (g)	18.04 ± 18.17	10.37 ± 4.12	*
CO_2eq(kg)	1.17 ± 0.78	1.00 ± 0.61	NS
CO_2 (kg)	2.28 ± 0.15	1.79 ± 0.20	*
H_2O (kg)	3.60 ± 0.11	2.96 ± 0.29	*
Batch 2[a]			
NH_3 (g N)	4.82 ± 0.66	6.68 ± 2.65	*
N_2O (g N)	4.04 ± 3.20	2.59 ± 3.20	NS
CH_4 (g)	8.88 ± 4.89	6.00 ± 3.24	NS
CO_2eq(kg)	2.08 ± 1.55	1.34 ± 1.56	*
CO_2 (kg)	2.11 ± 0.26	1.83 ± 0.64	*
H_2O (kg)	3.07 ± 0.64	2.66 ± 1.01	NS
Batch 3[a]			
NH_3 (g N)	6.64 ± 2.24	7.91 ± 0.77	NS
N_2O (g N)	2.52 ± 1.26	0.92 ± 0.53	**
CH_4 (g)	25.38 ± 20.55	13.07 ± 8.63	**
CO_2eq(kg)	1.75 ± 0.78	0.73 ± 0.42	**
CO_2 (kg)	2.62 ± 0.36	2.46 ± 0.37	NS
H_2O (kg)	4.30 ± 0.15	3.41 ± 0.24	NS
Batch 4[a]			
NH_3 (g N)	4.05 ± 0.83	4.78 ± 1.26	NS
N_2O (g N)	1.82 ± 2.00	2.01 ±1.64	NS
CH_4 (g)	8.56 ± 1.43	11.17 ± 3.56	NS
CO_2eq(kg)	1.04 ± 0.96	1.19 ± 0.84	NS
CO_2 (kg)	2.62 ± 0.50	2.41 ± 0.29	NS
H_2O (kg)	3.76 ± 0.94	3.37 ± 0.67	NS
Batch 1 to 4[b]			
NH_3 (g N)	5.37 ± 1.15	6.29 ± 1.32	**
N_2O (g N)	2.48 ± 1.12	1.78 ± 0.70	**
CH_4 (g)	15.21 ± 8.08	10.15 ± 2.99	***
CO_2eq(kg)	1.55 ± 0.52	1.11 ± 0.41	***
CO_2 (kg)	2.41 ± 0.26	2.12 ± 0.36	***
H_2O (kg)	3.68 ± 0.51	3.10 ± 0.36	***

***: P<0.001; **: P<0.01; *: P<0.05; NS: not significant; [a]: For each gas and each available surface, means ± standard deviation between the three periods of measurement; [b]: For each gas and each available surface, means ± standard deviation between the four batches

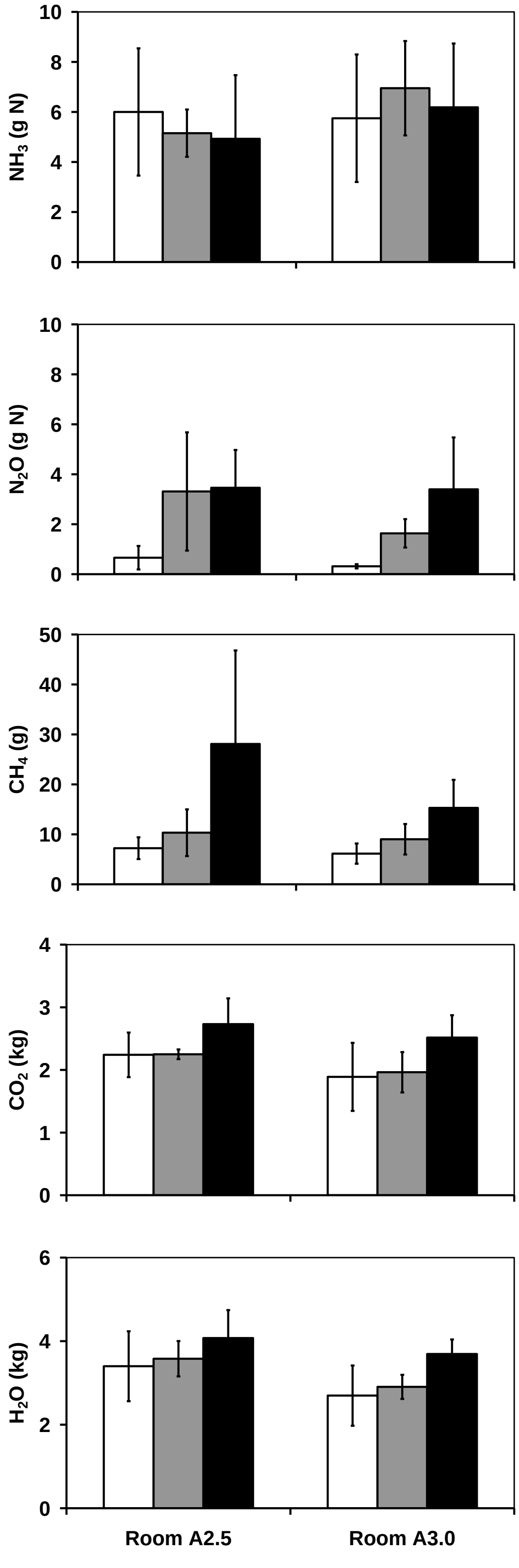

Figure 2 - Daily gas emissions per sow (mean ± standard deviation between the 4 batch) from deep litter pens with an available surface of 2.5 m² (Room A2.5) or 3.0 m² (Room A3.0) per gestating sow according to the gestation week (week 6: white; week 9: grey and week 12: black)

Nitrogen balance

Nitrogen balance (Table 6) is not significantly different between groups (*P*>0.05). . Feed provided nearby 90% of N-inputs. The main part of outputs is represented by N-manure with about 32 g N/d per sow (45% of outputs). N_2-emissions amount about 22 g N/d per sow for both animal density, corresponding to almost one third of total N-outputs.

Table 6 - Nitrogen balance (g N/d per sow) for group-housed gestating sows kept on deep litter with an available surface per sow of 2.5 m^2 (Room A2.5) or 3.0 m^2 (Room A3.0) (mean ± standard deviation between the 4 batches)

	Room A2.5	Room A3.0
N-inputs		
N-straw	8.2 ± 1.3 (12%)	8.2 ± 1.3 (12%)
N-feed	63.3 ± 5.5 (88%)	63.2 ± 4.6 (88%)
N-outputs		
N-retention (estimated)	9.5 ± 0.8 (13%)	9.5 ± 0.7 (13%)
N-manure	32.4 ± 4.9 (45%)	31.9 ± 12.1 (45%)
NH_3-N	5.4 ± 1.2 (8%)	6.3 ± 1.3 (9%)
N_2O-N	2.5 ± 1.1 (3%)	1.8 ± 0.7 (2%)
N_2-N (estimated)	21.8 ± 4.1 (30%)	22.0 ± 13.6 (31%)

4. Discussion

NH_3 emissions obtained in this experiment meet lower values presented in the literature ranging from 6 to 25 g NH_3–N/d per sow for grouped sow kept on litter (Groot Koerkamp *et al.*, 1998; Misselbrook *et al.*, 2000; Dore *et al.*, 2004). On slatted floor, cited values range from 5 g to 15 g NH_3-N/d per sow (Groot Koerkamp *et al.*, 1998; Groenestein *et al.*, 2003). Whatever the floor type, numerous factors can influence NH_3-emissions, like feeding management, interior climate, season and waste treatment (Harper *et al.*, 2004; Philippe *et al.*, 2006; Philippe *et al.*, 2009). Furthermore, for litter systems, properties of bedding materials (C/N ratio, carbon availability, pH value and physical structure, among others) affect volatilization (Jeppsson, 2002). Few studies evaluated effect of animal density on NH_3-emissions from sows on litter. With fattening pigs, Basset-Mens *et al.* (2007) observed twofold emissions while bedded space area is reduced by one-half. The authors explain the results by higher air temperature and ventilation rates associated to higher animal density. In the current study, these two climatic parameters are identical in both groups. With fattening pigs on slatted floor, Guingand (2007) observed a raise of emissions of 35% while space allowance increase by 43%. These results are accurately in accordance with the current experiment where increased space allowance of 20% is related with a raise of emissions of 17%. The explanation comes from the increase of exchange surface at the emitting area. Thus, increasing space allowance without modification of interior climatic conditions seems to have the same effect on NH_3-emissions whether pigs are kept on bedded or slatted floor.

About N_2O-emissions from gestating sows, few data are available in the literature. For fattening pigs, emission values reach 6.4 g N_2O-N/day with deep litter and are about 1.0 g N_2O-N/day with slatted floor (Basset-Mens *et al.*, 2007; Philippe *et al.*, 2007a). The formation of N_2O occurs during incomplete nitrification/denitrification processes that normally convert NH_3 into N_2. Nitrification requires aerobic conditions whereas denitrification requires anaerobic conditions. During denitrification, N_2O is synthesized in case of presence of oxygen or low availability of degradable carbohydrates or both (Poth and Focht, 1985). During nitrification, N_2O can be synthesized where there is a lack of oxygen or a nitrite accumulation or both (Veeken *et al.*, 2002). N_2O-synthesis needs thus close combination of aerobic and anaerobic areas, heterogeneous conditions met within the litter (Veeken *et al.*, 2002). These particular conditions explain higher emissions usually observed with bedded systems in comparison with slurry systems where the environment is largely anaerobic (Philippe *et al.*, 2007a; Cabaraux *et al.*, 2009). However, in bedded systems, N_2O-formation may be reduced in case of too aerobic litter due to generous straw supply (Kermarrec and Robin, 2002). In the current study, the increasing emissions with the course of time in both groups are also explained by the particular environment inside the litter. Throughout time, dejections are accumulated in the litter with creation of more anaerobic areas close to aerobic areas. Thus, the balance between aerobic and anaerobic areas within the litter is an important criterion influencing N_2O-emissions from bedded systems.

In this experiment, increasing available floor space from 2.5 m^2 to 3.0 m^2 reduce CH_4-emissions from 15 to 10 g/d per sow. In literature, large variations were observed between authors with values ranging from 5 to 60 g CH_4/d per sow (Groot Koerkamp and Uenk, 1997; Godbout *et al.*, 2003; Dong *et al.*, 2007). Methane originates from anaerobic degradation of organic matter in the digestive tract of animal and in the manure. Methanogenesis is mainly performed by mesophilic bacteria (25-40°C) with an optimal pH of 7.0-7.2 (Hellmann *et al.*, 1997). Enteric fermentations are enhanced by fibres intake (Philippe *et al.*, 2008; Philippe *et al.*, 2009). In manure, CH_4-release are promoted by high temperature and high DM content (Haeussermann *et al.*, 2006). Straw supply may enhance CH_4-emissions by increasing the DM-content and degradable carbohydrates content of the manure. Straw constitutes also a potential source of dietary fibres for the animals. On the other hand, straw may inhibit production because the too great aeration (Yamulki, 2006). As observed for N_2O, more anaerobic conditions could explain the increase of CH_4 emissions with the high animal density and with the course of time in both groups.

The emissions of CO_2eq calculated in this trial were reduced by about one third with the increase of the available space floor. This was due to the significantly and simultaneous decrease of direct N_2O and CH_4 emissions in the room A3.0. Direct N_2O and CH_4 represented 78% and 20% of total CO_2eq emissions respectively. So, even if the NH_3 emissions were greater in the room A3.0, its impact was negligible with about 2%.

The CO_2 production from piggeries originates mainly from the animal respiration but also from the manure releases. CO_2-exhalation by pigs is function of energy metabolism and can be derived from the heat production and the respiratory quotient (RQ, the ratio between the CO_2 production and O_2 consumption during respiration (Pedersen *et al.*, 2008). For gestating sows, CO_2 production at animal level is estimated at 0.165 m^3/h per 1000 W of total heat production, related to a RQ value of about 0.95 (Olesen *et al.*, 2001; Rijnen *et al.*, 2001; Theil *et al.*, 2002). According to the CIGR equations (CIGR, 2002), it corresponds to an exhalation of about 2.6 kg CO_2/d for the sows of the current essay. This estimated value is higher than the CO_2 emissions measured in this experiment. However, the CIGR equations are elaborated for daily gains around 0.18 kg/d over the entire gestation period and they are probably not adapted to the higher daily gain obtained in this experiment over a shorter period (0.72 kg/d from day 30 to day 100 of gestation). Moreover, important influencing factors like the feed intakes, diet composition and the animal activity may have also affected the CO_2-production by sows (Pedersen *et al.*, 2008). Nevertheless, the difference in CO_2-emissions between the two experimental groups seems to be explained rather by releases from manure than by respiration. CO_2-production in manure has two origins: the hydrolysis of urea leading to NH_3 and CO_2-production, and the anaerobic degradation of organic components which is the most important origin (Ni *et al.*, 1999). It is generally admitted that emissions are higher from litter than from slurry. With fattening pigs, they range from 0.15 to 0.54 kg CO_2/d with slatted floor (Ni *et al.*, 1999; Philippe *et al.*, 2007a) and from 0.35 to 1.40 kg CO_2/d with bedded floor (Jeppsson, 2000; Jeppsson, 2002; Philippe *et al.*, 2007a). In litter, the production is influenced by temperature, moisture content, carbon/nitrogen ratio (C/N ratio), pH level, oxygen level and the physical structure of the organic material (Jeppsson, 2000). CO_2 synthesis is promoted by high temperature but reduced by aerobic environment. Litter aeration related to space allowance could explain reduction of emissions measured in the room A3.0. In the same way, accumulation of dejection in the course of time explain higher emissions observed at the end of the experiment because of more anaerobic conditions within the litter. Besides, the present results showed that, although diet characteristics, feed intakes, animal performances and climate conditions are similar for both groups, CO_2-emissions may differ because of housing conditions. Former experiments carried out with weaning and fattening pigs reached to the same conclusion (Philippe *et al.*, 2007a and 2007b; Cabaraux *et al.*, 2009). Therefore, ignore CO_2 for the CO_2eq calculation and thus for the GWP evaluation of livestock farming systems may be debatable.

Like CH_4 and CO_2, H_2O emissions have two origins: animals and manure. Evaporation by animals is function of body weight, heat production and ambient temperature (CIGR, 2002) and evaporation from manure is function of litter temperature related to the level of the fermentations. In the current experiment, the room A2.5 emitted about 0.6 kg H_2O more than the room A3.0. As the A2.5 sows drank about 0.6 l water more than the A3.0 sows and as the manure characteristics did not differ between groups, it was thus normal to find greater H_2O emissions from room A2.5. However, in room A2.5, the observation of greater amount of water in emissions could probably be also explained by greater litter temperatures (not measured in this trial) due to the reduced area, to the higher litter depth and to the greater amount per m^2 of heat supplied by sows during the sleep.

5. Conclusion

An increase of the available area for group-housed gestating sow kept on straw based deep litter did not modify manure characteristics and performance at short term.

However, despite a good brand image for the consumer and a welfare improvement for the sows, environmental impacts of this system seem to be ambiguous.

Compared with a conventional and legal available area, greater available area favours NH_3 emissions probably due to increased emitting surface. However, about greenhouse gases, it decreases N_2O, CH_4 and CO_2 emissions probably due to reduced anaerobic conditions required for their synthesis and leads to a reduction of CO2eq emissions.

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4. Effets de la quantite de paille sur les emissions gazeuses associees a l'engraissement de porcs charcutiers sur litiere de paille accumulee

L'influence de la quantité de paille sur les émissions gazeuses en porcherie avait été avancée pour expliquer la différence de résultats entre porcs charcutiers et truies gestantes quant à l'effet du mode d'hébergement, caillebotis ou litière, sur les émissions de NH_3. En effet, avec les porcs charcutiers et un paillage équivalent à 390 g jour^{-1} porc^{-1}, la production de NH_3 avait été plus élevée dans le système paillé, alors qu'avec les truies gestantes et un paillage de 920 g jour^{-1} truie^{-1}, les émissions ont été réduite en comparaison au système latté, l'estimation des rejets azotés totaux étant similaire pour les deux types d'animaux. Par ailleurs, l'effet du taux de paillage sur les émissions de GES restait à déterminer. Dès lors, l'objectif de cette étude était de comparer l'impact de la quantité de paille (50, 75 ou 100 kg par porc) sur les émissions de NH_3, N_2O, CH_4 et CO_2 lors de l'engraissement de porcs charcutiers sur litière accumulée.

Trois bandes successives de 30 porcs charcutiers (Piétrain x Landrace belge) ont été divisées en trois groupes identiques hébergés dans trois loges séparées, d'une superficie de 12,6 m^2 chacune. Le paillage initial et des apports hebdomadaires successifs ont aboutit à une quantité de paille de 500, 750 et 1000 kg en fin d'engraissement, respectivement dans les trois loges. Les mesures d'émissions gazeuses ont été effectuées par détection photo-acoustique infrarouge (INNOVA 1412) durant 3 périodes de 6 jours consécutifs réparties sur l'ensemble de chaque période d'engraissement.

En augmentant les apports de pailles de 50 à 100 kg porc^{-1}, les émissions de NH_3 ont été réduites (16,04 *versus* 19,04 g NH_3 porc^{-1} jour^{-1}, $P<0,001$) probablement en raison de propriétés particulières de la litière (comme par exemple la température et le rapport C/N) qui ont favorisé l'assimilation de l'azote en protéines bactériennes plus stables. Ce constat contribue à expliquer la différence observée entre les deux études portant sur l'effet du type de sol sur les émissions de NH_3 associées à l'élevage de porcs charcutiers et de truies gestantes. Concernant les GES, le paillage le plus important a induit une réduction des émissions de N_2O (0,74 *versus* 1,11 g N_2O porc^{-1} jour^{-1}, $P<0,001$) qui, en terme d'Eq-CO_2, a été compensée par une augmentation des émissions de CH_4 (9,09 *versus* 4,83 g CH_4 $porc^{-1}$ $jour^{-1}$, $P<0,001$). L'aération des litières et l'apport de matière organique fermentescible peuvent expliquer ces résultats. Les émissions de CO_2 ont été peu impactées par le taux de paillage avec 2,40-2,50 kg CO_2 $porc^{-1}$ $jour^{-1}$, $P>0,05$).

Effets de la quantité de paille sur les émissions d'ammoniac et de gaz à effet de serre lors de l'élevage de porcs charcutiers sur litière accumulée

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Abstract

This trial aims to study the effect of the amount of straw on emissions of ammonia (NH_3), nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2) associated with fattening pigs kept on deep litter. Three successive batches of 30 fattening pigs (Piétrain x Belgian Landrace) were divided into three similar groups that were housed separately in three identical experimental rooms fitted with a bedded floor pen of 12.6 m^2 of available area (1.26 m^2 per pig). In each room, the initial deep litter was made of 250 kg of whole wheat straw constituting a layer of about 30 cm depth. Thereafter, fresh straw was supplied once a week up to a total amount of 500, 750 or 1000 kg at the end of the fattening periods (96 days). Manures were removed after each fattening period. Ventilation was controlled to maintain a constant ambient temperature. The gas emissions were measured by infrared photoacoustic detection (3 measurement episodes of 6 consecutive days for each fattening period, with 3 weeks of interval between measurement episodes). Increasing the amount of straw from 50 to 100 kg per pigs significantly reduced the emissions of NH_3 (16.04 vs. 19.04 g NH_3 pig^{-1} day^{-1}, $P<0.01$) and N_2O (0.74 vs. 1.11 g N_2O pig^{-1} day^{-1}, $P<0.001$) but increased the emissions of CH_4 (9.09 vs. 4.83 g CH_4 pig^{-1} day^{-1}, $P<0.001$). CO_2-emissions were less impacted by the amount of straw with about 2.45 kg CO_2 pig^{-1} $day^{-1}$for the three treatments ($P>0.05$).

1. Introduction

Les émissions de gaz polluants associées à l'hébergement de porcs sur litière sont fortement influencées par les conditions physico-chimiques rencontrées au sein des fumiers (Philippe *et al.*, 2012). Ainsi, la quantité de paille peut avoir un impact important sur les niveaux d'émissions. L'objectif de cette étude est de comparer l'effet de la quantité de paille sur les émissions d'ammoniac (NH_3), de protoxyde d'azote (N_2O), de méthane (CH_4) et de dioxyde de carbone (CO_2) lors de l'engraissement de porcs charcutiers sur litière accumulée.

2. Matériel et méthodes

Trois bandes successives de 30 porcs charcutiers (Piétrain x Landrace belge) ont été divisées en trois groupes identiques hébergés dans trois loges séparées, d'une superficie de 12,6 m^2 chacune (1,26 m^2/porc). En début d'engraissement, 250 kg de paille de blé étaient disposés dans chaque loge afin de constituer la couche initiale de paille (environ 30 cm). Ensuite, de la paille était apportée une fois par semaine pour atteindre une quantité totale de paille de 500, 750 et 1000 kg en fin d'engraissement (96 jours), respectivement dans les trois loges. Les locaux étaient ventilés de manière contrôlée avec enregistrement en continu des températures ambiantes et des taux de ventilation. Un aliment commercial identique pour les trois groupes sur l'ensemble de l'engraissement était apporté aux animaux (protéines brutes : 16,0%, énergie nette : 9,33 MJ/kg). Entre chaque bande, les fumiers étaient évacués et les loges nettoyées. Les concentrations en gaz (NH_3, N_2O, CH_4, CO_2) ont été mesurées par détection photo-acoustique infrarouge (INNOVA 1412) durant 3 périodes de 6 jours consécutifs réparties sur l'ensemble de chaque période d'engraissement. Les émissions d'équivalent CO_2 (Eq-CO_2) ont été calculées selon les recommandations de l'IPCC (IPCC, 2006). Les données horaires d'émission ont été testées par analyse de la variance grâce à un modèle mixte pour données répétées (144 valeurs (24 heures x 6 jours) par période de mesure) en tenant compte de la quantité de paille (2 d.l.), de la période de mesure (2 d.l.) de l'interaction quantité période (2 d.l.), et du lot comme effet aléatoire (SAS, proc MIXED).

3. Résultats

La température moyenne dans les locaux expérimentaux a été de 20,0 $\pm$ 0,7°C, le débit de ventilation de 74,6 $\pm$ 15,5 m^2/heure.porc, et l'humidité relative de 56,3 $\pm$ 2,2 %. En début d'expérience, les porcs avaient un poids corporel moyen de 36,3 ± 1,0 kg pour atteindre 112,9 ± 2,2 kg en fin d'engraissement. Le tableau 1 reprend les niveaux d'émissions gazeuses mesurées dans les deux locaux.

Tableau 1 –Effet de la quantité de paille sur les émissions gazeuses (/porc.jour) mesurées lors de l'engraissement de porcs charcutiers sur litière accumulée (NH_3, ammoniac ; N_2O, protoxyde d'azote ; CH_4, méthane ; Eq-CO_2, équivalent-CO_2 ; CO_2, dioxyde de carbone)

	Quantité de paille			**e.s.**[a]	**Sign.**[b]
	50 kg	**75 kg**	**100 kg**		
NH_3 (g)	$19{,}04^{x}$	$18{,}24^{x}$	$16{,}04^{y}$	0,56	**
N_2O (g)	$1{,}11^{x}$	$0{,}87^{y}$	$0{,}74^{z}$	0,04	***
CH_4 (g)	$4{,}83^{x}$	$7{,}33^{y}$	$9{,}09^{z}$	0,11	***
Eq-CO_2 (g)	529,4	514,7	511,7	8,2	NS
CO_2 (kg)	2,40	2,50	2,46	0,03	NS

[a] : Erreur standard ; [b] : Signification : NS : P>0,05 ; ** : P<0,01 ; *** : P<0,001 ; [x, y, z] : Dans une même ligne, les nombres agrémentés de lettres différentes diffèrent significativement entre eux.

4. Discussion

Les émissions de NH_3 ont été diminuées de 16% en augmentant la quantité de paille de 50 à 100 kg par porc, confirmant ainsi les résultats de Gilhespy *et al.* (2009) et Guingand et Rugani (2013). Ces derniers avaient observé une réduction de près de 25% de la production de NH_3 en passant de 60 à 90 kg de paille par porc. En fait, l'apport de substrat supplémentaire permet d'augmenter la teneur en carbone des litières ce qui favorise l'assimilation bactérienne de l'azote alors rendu moins disponible pour la synthèse de NH_3.

De même, les émissions de N_2O ont été significativement réduites (-33%) avec le paillage le plus important, ce qui rejoint les observations de Yamulki (2006) et Guingand et Rugani (2013). Ce résultat pourrait s'expliquer par une aération et une température plus élevées à l'intérieur des litières, facteurs connus pour limiter la synthèse de N_2O (Sommer *et al.*, 2000).

A l'inverse, les émissions de CH_4 sont augmentées significativement (+188%) avec des quantités croissantes de paille, ce qui confirme les résultats de Guingand et Rugani (2013) mais contredit ceux de Yamulki (2006) et Sommer *et al.* (2000). Les premiers expliquaient l'augmentation des émissions par l'accroissement de la quantité d'hydrate de carbone disponible pour les bactéries méthanogènes alors que les derniers justifiaient la réduction des émissions par une aération trop importante de la litière qui limitait la production de CH_4. Le taux de paillage, en modifiant l'aspect et surtout la propreté de la litière, peut également influencer son niveau d'ingestion par les animaux, et par conséquent la production entérique de CH_4, qui dépend de la quantité de fibres consommées.

Les émissions cumulées de N_2O et CH_4, exprimées en Eq-CO_2, ne montrent pas de différence significative entre les trois traitements, la production plus élevée de CH_4 étant compensée par la réduction des émissions de N_2O.

Les émissions de CO_2 ont été également similaires pour les trois quantités de paille testées, avec environ 2,45 kg/porc.jour. La production respiratoire, qui dépend du poids corporel des porcs et de leur métabolisme, en est la principale source, la contribution des fumiers étant plus faible.

5. Conclusion

Dans le système d'hébergement de porcs sur litière accumulée, augmenter la quantité de paille de 50 à 100 kg par porc engraissé permet de réduire significativement les émissions de NH_3. Concernant les gaz à effet de serre (GES), la diminution des émissions de N_2O observée avec le paillage le plus important est contrebalancée par l'augmentation des émissions de CH_4, avec globalement des émissions cumulées de GES identiques. Les émissions de CO_2 semblent peu influencées par le taux de paillage. Les impacts du paillage sur le coût de production mais également sur le bien-être des animaux et l'image de marque pour le consommateur devront également être pris en compte dans le choix d'un mode d'hébergement.

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5. Emissions d'ammoniac et de gaz a effet de serre associees a l'engraissement de porcs charcutiers sur litiere de paille accumulee ou litiere glissante

Les études précédentes ont montré que les émissions de gaz polluants à partir des systèmes avec litière pouvaient fortement varier en fonction de facteurs tels que la surface disponible et le taux de paillage. Plus globalement, le mode de gestion de l'effluent influence les niveaux d'émissions en modifiant les caractéristiques physico-chimiques au sein des fumiers. Ainsi, la technique d'hébergement sur litière regroupe un grand nombre de modalités différentes qui varient en fonction de la nature du substrat utilisé (paille, sciure et copeaux de bois, tourbe,...), de la fréquence et de l'importance des apports et du type d'évacuation des fumiers (litière accumulée, litière raclée,...) (Ramonet et Dappelo, 2003). Parmi ces techniques, l'élevage sur litière glissante, aussi appelée pente paillée ou « Straw-flow », consiste à loger les porcs sur un sol en pente et à apporter régulièrement de la paille au sommet de la pente (Bruce, 1990). Grâce à l'activité des porcs, cette paille se mélange aux déjections et glisse le long de la pente jusqu'à un couloir de raclage d'où elle est évacuée fréquemment. En comparaison au système sur litière accumulée où le fumier n'est évacué qu'après plusieurs mois, ce type de logement permet de réduire le besoin en surface, paille, main d'œuvre et volume de stockage des fumiers, tout en apportant aux animaux suffisamment de matériel manipulable afin d'exprimer leurs comportements d'exploration et de mâchonnement. L'effet de ce mode d'hébergement sur les facteurs environnementaux n'ayant fait l'objet que de peu de recherche, l'objectif de cette étude était de comparer les émissions de NH_3, N_2O, CH_4 et CO_2 lors de l'engraissement de porcs sur litière de paille accumulée ou litière glissante.

Pour cette étude, deux locaux expérimentaux, similaires en volume (103 m^3) et en surface (30 m^2), ont été équipés afin d'héberger des groupes de 16 porcs charcutiers soit sur litière de paille accumulée, soit sur litière glissante. Dans la loge avec paille accumulée, la surface disponible était de 19,2 m^2. La quantité initiale de paille était de 375 kg représentant une couche d'environ 30 cm. Des apports réguliers de paille à intervalle d'environ 2 semaines ont porté la quantité totale à 750 kg par période d'engraissement. Les fumiers étaient évacués en fin d'engraissement. Dans la loge avec litière glissante, la surface disponible était de 12,0 m^2. La paille apportée quotidiennement au sommet de la pente en sol bétonné représentait en fin d'engraissement une quantité totale de 550 kg. La partie liquide de l'effluent était pompée automatiquement depuis le couloir de raclage vers un réservoir hermétique alors que la partie solide était raclée quotidiennement, stockée dans le local et évacuée chaque mois. Trois bandes successives de 32 porcs charcutiers (Piétrain x Landrace belge), répartis uniformément en deux groupes en fonction du poids et du sexe, ont été hébergés dans ces locaux. D'un poids initial de 23 kg, les porcs ont été engraissés durant environ 4 mois jusqu'à un poids final proche de 115 kg. La ventilation des locaux se faisait au moyen de ventilateurs extracteurs (un par local) et de manière contrôlée avec adaptation automatique du débit de ventilation en fonction de la température, ces deux paramètres étant mesurés et enregistrés en continu (Fancom, Panningen, Pays-Bas). Les concentrations en gaz ont été mesurées dans les locaux expérimentaux et dans le couloir d'apport d'air par détection photo-acoustique infrarouge au moyen d'un moniteur équipé pour la mesure simultanée de NH_3, N_2O, CH_4, CO_2 et H_2O (1312 Photoacoustic Multi-Gas Monitor, Innova Air Tech Instruments, Nærum, Denmark). Quatre séries de mesures de six jours consécutifs réparties de manière homogène sur la période d'engraissement ont été réalisées pour chaque bande de porcs. Les émissions (E_{gaz}) ont été calculées sur base horaire grâce à l'équation suivante :

$E_{gaz} = D \times (C_i - C_e)$,

avec D, le débit de ventilation (kg air h^{-1}), et C_i et C_e, respectivement la concentration en gaz dans l'air du local expérimental et du couloir d'apport d'air (mg kg^{-1} air). Les résultats d'émissions ont été testés au moyen d'un modèle mixte pour données répétées (SAS, Mixed Proc) en incluant l'effet du type de sol (1 dl), de la série de mesure (3 dl), de l'interaction sol-série (3 dl) et du lot comme effet aléatoire avec 144 données (24 heures x 6 jours) par série de mesure.

Les émissions de NH_3 ont été plus élevées avec la litière glissante en comparaison à la litière accumulée (13,3 *versus* 12,1 g NH_3 $porc^{-1}$ $jour^{-1}$, $P<0,05$), malgré la séparation des phases liquide et solide, l'évacuation fréquente de l'effluent et la surface disponible plus faible, trois facteurs connus pour réduire les émissions de NH_3 (Godbout et al., 2006 ; Guingand, 2007). En fait, des études ont montré que l'activité de l'uréase, enzyme qui convertit l'urée en NH_3, était rapide avec des pics importants d'émission 2-3 h après application d'urine sur un sol bétonné (Braam et Swierstra, 1999; Groenestein *et al.*, 2007). Le mode d'évacuation de l'effluent tel qu'appliqué dans cette expérience n'empêche donc pas la formation précoce de NH_3. De plus, la manipulation journalière des fumiers lors des activités de raclage, le faible taux de paillage et le stockage temporaire des fumiers dans le local ont contribué aux émissions plus importantes observées avec la litière glissante.

Les émissions de N_2O et de CH_4 ont été plus faibles avec la litière glissante en comparaison à la litière accumulée (0,68 *versus* 1,50 g N_2O porc^{-1} jour^{-1}, $P<0{,}001$; 8,9 *versus* 16,5 g CH_4 porc^{-1} jour^{-1}, $P<0{,}001$). Le caractère plus aéré de la litière au niveau de la loge, mais également au niveau du tas de fumier stocké dans le local en raison des manipulations journalières de raclage et l'absence de tassement par les animaux, peut expliquer ce résultat. En effet, il a été démontré qu'une litière plus poreuse réduisait à la fois la production de N_2O et de CH_4 (Kermarrec et Robin, 2002 ; Yamuki, 2006). Par ailleurs, la formation de CH_4 lors des fermentations entériques a été évaluée à environ 3 g porc^{-1} jour^{-1} en tenant compte de la teneur en fibre de l'aliment (Le Goff, 2001 ; Vermorel et al., 2008).

Les émissions de CO_2 ont également été réduites à partir de la loge à pente paillée (1,77 *versus* 1,97 kg CO_2 porc^{-1} jour^{-1}, $P<0{,}001$). La production respiratoire par les animaux, qui dépend du métabolisme, et donc du poids corporel et des ingestions alimentaires, a été estimée à environ 1,6 kg CO_2 porc^{-1} jour^{-1} pour les deux types de logement (Ni et al., 1999a ; CIGR, 2002 ; Pedersen et al., 2008). La différence observée pourrait avoir comme origine des conditions particulières rencontrées au sein des litières. La température, la teneur en humidité, le rapport C/N, la dégradabilité de la matière organique, le pH et la structure physique de l'effluent sont en effet des caractéristiques qui interagissent entre elles pour moduler le niveau de production de CO_2 à partir des litières (Andersson, 1996; Jeppsson, 2000; Paillat et al., 2005).

En conclusion, l'hébergement de porcs charcutiers sur sol à pente paillée tel que testé dans cette étude est associé à une augmentation des émissions de NH_3 combinée à une réduction des émissions des GES (N_2O, CH_4 et CO_2), en comparaison à la litière de paille accumulée. La formation rapide de NH_3 n'a pu être empêchée malgré la séparation des phases liquides et solides et l'évacuation fréquente des effluents. La plus faible production de GES peut s'expliquer par les propriétés physico-chimiques des litières.

Ammonia and greenhouse gas emissions during the fattening of pigs kept on two types of straw floor

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Keywords

Ammonia - Fattening pigs - Greenhouse gases - Deep litter - Straw flow - Water vapour

Abstract

Pig production is an important contributor to polluting gases emissions like ammonia (NH_3) and greenhouse gases (GHG). Apart from environmental aspects, animal welfare is also an issue of growing importance. The fattening of pigs on deep litter bedded system is consider as more animal friendly than the fattening on slatted floor, but it is also more expensive and requests more labour. The use of straw flow rather than straw deep litter could be a good compromise because of a reduced need for surface area, straw, labour and manure storage, combined with satisfying animal welfare. In order to evaluate the environmental impact of this rearing technique, a study was designed to quantify pollutant gas emissions of this system compared to the deep litter system for fattening pigs. Three successive batches of 32 Landrace fattening pigs were used. They were divided into 2 homogeneous groups of 16 animals randomly allocated to two treatments: straw deep litter or straw flow. The groups were kept simultaneously for a period of 4 months and separately in two identical rooms in volume (103 m^3) and surface (30.2 m^2) and fitted either with a deep litter pen (1.2 m^2 per pig) or with a straw flow system (0.75 m^2 per pig). Throughout the fattening period, 46.9 and 34.4 kg straw were used respectively per pig. In deep litter pen, the litter was removed after each batch. In the straw flow pen, the straw, mixed with dung, travelled down the slope by pig motion and went out of the pen to a scraped passage. The solid fraction was scraped every day, stored in a heap in the room and removed every month, 1 week before each

period of gaseous emission measurement. The liquid fraction was automatically pumped from the scraped passage into a hermetic tank, which was emptied at the end of each fattening period. In both rooms, ventilation was automatically adapted to maintain a constant ambient temperature. Once a month, the emissions of ammonia (NH_3), nitrous oxide (N_2O), methane (CH_4), carbon dioxide (CO_2), and water vapour (H_2O) were measured continuously for 6 consecutive days by infra-red photoacoustic detection.
Animal performance (final body weight, body weight gain, and feed conversion ratio), some carcass quality parameters and manure characteristics were not significantly affected by floor type. With fattening pigs kept in a straw flow pen, gaseous emissions were significantly greater ($P < 0.05$) for NH_3 (+10%) and significantly lower ($P < 0.001$) for N_2O (-55%), CH_4 (-46%), CO_2 equivalents (-47%), CO_2 (-10%) and H_2O (-23%) compared to pigs housed on straw-based deep litter.
Thus, the use of straw flow system for pig fattening allows reducing the GHG emissions but presents the disadvantage of increasing the NH_3 emissions.

Highlights

- The litter management (amount of substrate, frequency of supply, removal strategy ...) greatly impact the emissions of pollutant gases.
- Compared to the straw-based deep litter system, the straw flow system is associated to higher NH_3-emissions while the N_2O-, CH_4-, CO_2-and H_2O-emissions are reduced.
- The animal performance and the manure characteristics were not greatly influenced by the type of straw litter.

1. Introduction

Livestock productions significantly contribute to polluting gases emissions like ammonia (NH_3) and greenhouse gases (GHG). Ammonia accelerates the fine particulates formation in the atmosphere and is implicated in eutrophication of fragile ecosystems and soil acidification (Krupa, 2003). Greenhouses gases, including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), participate in global warming and climate change. Nitrous oxide also contributes to the depletion of stratospheric ozone layer (IPCC, 2007). Globally, the livestock sector is responsible for about 65% of the anthropogenic emissions of NH_3 and 18% of the anthropogenic emissions of GHG, including energy consumption and land-use change (Steinfeld *et al.*, 2006). Nevertheless, large imprecision remains in the magnitude of these pollutant gas emissions under particular field conditions (Reidy *et al.*, 2009). For pigs kept on litter, uncertainties in emission levels come partly from the numerous kinds of bedded systems and the complex interactions observed in the litter (Webb *et al.*, 2005; IPCC, 2006). For instance, a recent review article about NH_3 emissions from pig houses (Philippe *et al.*, 2011a) fails to reach a consensus in favour/disfavour of a floor type comparing slatted and bedded systems. About N_2O emissions, if they are considered negligible from slurry, they are favoured in the litter, but large variations are observed between bedded systems (Jungbluth *et al.*, 2001; Rigolot *et al.*, 2010). Therefore, researches are greatly needed to obtain accurate emissions factors for litter systems and to refine the precision of inventories according to litter management and type of substrate.

Apart from the environmental issues, livestock production systems have to meet the market demand for improved animal welfare, while maintaining economic profitability. In pig production, bedded systems are known to support animal welfare, principally as they yield substrate for expressing behaviours that pigs are strongly motivated to perform like rooting and chewing (Tuytens, 2005). It is estimated that the cost of rearing pigs on litter-based systems is 5 to 10% greater than slatted floor systems because the costs of substrate and the increased in labour cost outweigh the lower building costs (Philippe *et al.*, 2006b). A large range of bedded systems are described differing by substrate type and litter management. The most frequent substrate is straw, but sawdust, wood shavings or even paper are also used (Andersson, 1996). Litter may be regularly scraped or may be accumulated under animals and removed after one or several animal batches (Ramonet and Dappello, 2003). This latter system is called 'deep litter'. In the 1990s, Bruce (1990) developed a particular bedded system, the 'straw flow'. With this system, straw is supplied at the top of a sloped lying area and, with the aid of pig motion, it travels down the slope, is mixed with dung and goes through a dung fence to a scrapped passage outside the pen. This floor type gives the benefit of a reduced need for surface area, straw, labour and manure storage.

Thus, the aim of this paper is to compare the emissions of NH_3, N_2O, CH_4 and CO_2 during the fattening of pigs kept on straw-based deep litter or on straw-flow. Water vapour (H_2O) emissions from the two systems were also measured, as these emissions are a key factor in determining the ventilation needs of animal buildings, especially with bedded systems, in order to avoid excessive relative humidity that is deleterious for animal health and performance (CIGR, 2002; Banhazi *et al.*, 2008).

2. Materials and methods

The trial was carried out in an experimental unit located at the Faculty of Veterinary Medicine of the University of Liège (Belgium). The ethical committee of the institution approved the use and treatment of animals in this study.

2.1 Experimental rooms

Two experimental rooms, similar in volume (103 m^3) and surface (30.2 m^2), were arranged for this experiment. One room was equipped with a straw-based deep litter pen (DL) and the other one with a straw-flow system pen (SF) (Figure 1). Each pen had a capacity for 16 pigs with an available floor space of 1.2 m^2 per pig kept on DL and 0.75 m^2 per pig kept on SF. Three successive batches of pigs were fattened during the experiment. Before each fattening period, in DL pen, 375 kg of whole wheat straw (23.4 kg per pig) was used to constitute the initial deep litter of about 30 cm depth. Throughout the fattening period, fresh straw was supplied regularly up to a total amount of 750 kg (46.9 kg per pig). At the end of each fattening period, litter was removed, weighed and sampled. The concrete straw-flow system used in this experiment was an adaptation from the system described by Bruce (1990). The pen was made up of a flat area 0.5 m wide with feeders, together with a lying area of 2.83 m with a slope of 6%, separated by a step of 10 cm of a dunging area 0.91 m wide with a slope of 10%. Long whole wheat straw was manually supplied daily at the top of the slope. The amount of straw used per fattening period was 550 kg (34.4 kg per pig). The scraped passage was 20 cm beneath the pen level. Liquid from manure was automatically pumped from the scraped passage into a hermetic tank. The rest of the manure was manually scraped every day and stored in the room. The manure heap was removed, weighed and sampled every month, 1 week before the beginning of each period of gaseous emission measurement. Liquid in the tank was removed, weighed and sampled at the end of each fattening period. In between each batch, the two pens were cleaned. The samples of manure from DL pen and of liquid and solid manure from SF pen were analysed in order to determine dry matter (DM) and N content (Kjeldahl method).

Each room was ventilated with an exhaust fan (Fancom, Panningen, The Netherlands) and the ventilation rate was adapted automatically to maintain a constant ambient temperature by means of regulator FCTA (Fancom, Panningen, The Netherlands). Fresh air entered through an opening of 0.34 m^2, which was connected to the service corridor of the building; the outside air was thereby preheated before entering the experimental rooms. The air temperatures of the experimental rooms, the corridor and the outside were automatically measured every hour by NTC thermistors. The ventilation rates were measured continuously and the hourly means were recorded with an Exavent apparatus (Fancom, Panningen, The Netherlands) with accuracy of $35 m^3 h^{-1}$, that is 1% of the maximum ventilation rate of the fan.

2.2. Animals and feed

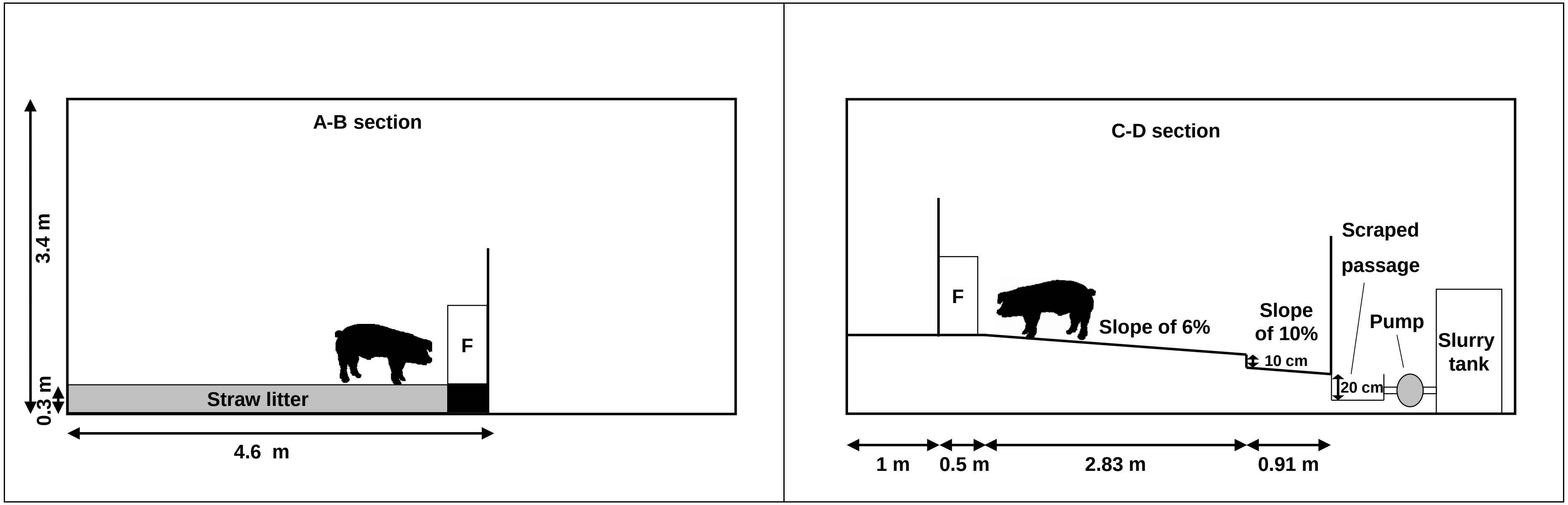
Three successive batches of 32 Piétrain×Belgian Landrace weaned pigs were used. They were divided into 2 homogeneous groups of 16 animals according to the age, the sex and the body weight. Each group was randomly allocated to a treatment: stay in room 1 on straw-based deep litter or in room 2 on straw-flow system. The groups were kept simultaneously for a period of about 4 months. Pigs were fed *ad libitum* with commercial growing meal, followed after about 40 days by a finishing meal (Table 1). The meals were the same for the two groups during the same fattening batch, but differed slightly from one batch to another. Cereals represented about two-thirds of the diet and soya-bean meal about 20%. Crude protein content was 18.1% for the growing meal and 15.6% for the finishing meal. Diets were balanced in amino acids. The feeding equipment was composed of two single-spaced feeders per pen with an integrated watering nipple. In the pen with the sloped floor, an extra watering device was placed at the bottom of the slope to encourage animals to dung in this area (Figure 1). Pigs were weighed individually at the beginning and at the end of each fattening period, enabling the measurement of individual average daily gains. Meters (Wateau®, EEC approval no. B02 314.29) were used to determine the water consumption per pen (including potential spillage but not cleaning water). Feed and water intakes and feed conversion ratio were determined per group. At the slaughterhouse, carcass weights, lean yield percentages measured using the CGM optical method (Capteur de Gras Maigre, Sydel, France) and carcass prices were determined individually.

Table 1 - Composition of the experimental diets

	Growing diet	**Finishing diet**
Ingredients (%)		
Barley	25.0	10.0
Soybean meal	24.8	11.1
Wheat	10.2	37.0
Corn	10.0	19.2
Rye	9.0	-
Oat	8.0	-
Peas	6.0	8.5
Fat	2.3	-
Sugar beet molasses	2.0	-
Mineral-vitamin complex[a]	1.5	1.5
Limestone	0.6	0.6
Dicalcium phosphate	0.3	-
L-Lysine	0.1	-
DL-Methionine	0.1	-
Copper sulphate	0.1	-
Wheat bran	-	4.1
Palm kernel meal	-	3.0
Rapeseed meal	-	2.5
Chicory pulp	-	2.0
Soybean oil	-	0.5
Chemical composition (%)		
Dry matter	87.5	87.3
Crude protein	18.1	15.6
Crude fat	4.7	2.9
Crude ash	5.3	4.2
Crude cellulose	5.0	4.7
Starch	36.1	44.2
Sugars	5.0	3.4
Net energy (kJ kg^{-1})	9316	9380

[a]: Provided the following nutrients per 1 g of premix: Vitamin (Vit.) A, 667 IU; Vit. D3, 133 IU; Vit. E, 5.33 mg; Vit. B1, 0.07 mg; Vit. B2, 0.20 mg; Vit. B3, 0.67 mg; Vit. B6, 0.13 mg; Vit. B12, 2 μg; Vit. PP, 1.33 mg; Biotin, 3 μg; Vit. K, 0.07 mg; Folic acid, 0.03 mg; Cholic acid, 6.63 mg; Fe, 6.67 mg; Cu, 1.00 mg; Mn, 2.67 mg; Co, 0.07 mg; Zn, 6.67 mg; I, 0.13 mg; Se, 0.03 mg; 6-Phytase, 48 FYT.

Figure 1 - Plan of the experimental rooms (F: feeding trough; W: water trough; EF: exhaust fan)



2.3. Gas emissions measurement

The concentrations of gases in the experimental rooms and in the corridor supplying fresh air were measured by infrared photoacoustic detection with a multigas monitor – INNOVA 1312 (LumaSense Technologies A/S, Ballerup, Denmark) equipped and calibrated for simultaneous measurement of NH_3, N_2O, CH_4, CO_2 and H_2O. The lower levels of detection were 0.2 ppm for NH_3, 0.03 ppm for N_2O, 0.1 ppm for CH_4 and 3.4 ppm for CO_2, with an accuracy rate of 95%, in accordance with ISO 6142 and ISO 1995. The air in the experimental rooms was sampled just upstream of the exhaust fan and that one of the corridor, at 1m from the air inlet. The air was analysed every hour. During the raising of each batch, four measurement series of 6 consecutive days were conducted with a 1-month interval between the series. The first series began 3 weeks after the arrival of the pigs.

For each gas, the emissions (E_{gas}), expressed in mg h^{-1}, were calculated on a hourly basis according to the following formula:

[1] $E_{gas} = D \times (C_{in} - C_{out})$

with D, the hourly mass flow (kg air h^{-1}); C_{in} and C_{out}, respectively, the concentrations of gas in the air of the experimental room and corridor (mg kg^{-1} dry air). The mean emissions per day and per pig were calculated for each series of measurements. Emissions were also expressed per livestock unit (LU, equals to 500 kg body weight), based on an average pig weight calculated as the mean between the initial and the final body weight.

The global warming potential of the GHG, N_2O and CH_4 together, was expressed in CO_2 equivalents (CO_{2eq}). CO_2-emissions were excluded from this estimation because IPCC (2006) estimated that CO_2 production by livestock is compensated by CO_2 consumption by photosynthesis of plants used as feed. However, indirect N_2O-emissions from atmospheric deposition of nitrogen (N) from NH_3 on soils and water surfaces have been added to the direct N_2O-emissions. The indirect emissions were calculated considering an emission of 0.01 kg N_2O-N kg^{-1} emitted NH_3-N (IPCC, 2006). The emissions of CO_{2eq} (kg d^{-1} pig^{-1}) were thus calculated using the following equation:

[2] $E_{CO2eq} = 25\ E_{CH4} + 298\ (E_{N2O} + 0.01\ E_{NH3\text{-}N} * 44/28)$

taking into account that the warming potentials of CH_4 and N_2O over a 100-year period are, respectively, 25 and 298 times that of CO_2 (IPCC, 2007).

2.4. Nitrogen balance

Nitrogen balance (g N day^{-1} pig^{-1}) was calculated for each group with inputs corresponding to N-straw and N-feed and outputs corresponding to N-manure, N-NH_3, N-N_2O and unaccounted-N. N-straw was determined taken into account a protein content of 38.6 g kg^{-1} (Sauvant et al., 2004). N-feed values were based on diet composition and consumption by pigs. The determination of N-manure, N-NH_3 and N-N_2O was described above. Unaccounted-N, as default value, was calculated by the following equation:

[4] Unaccounted-N = (N-straw + N-feed) - (N-manure + N-NH_3 + N-N_2O + N-retention)

N-retention was estimated by the following equation based on lean meat percentage (LM, expressed in %) and average daily gain (ADG, expressed in g d-1) (CORPEN, 2003):

[3] $\text{N-retention} = e^{(-0.9385-0.0145\times \text{LM})} \times (0.915\ \text{ADG}^{1.009})^{(0.7364+0.0044\times \text{LM})}/6.25.$

2.5 Statistical analyses

For animal performance data recorded per pig, the differences between groups housed on 2 different floors (DL *vs.* SF) were tested using analysis of variance with 2 criteria (proc GLM) (SAS, 2005): floor (1 df), batches (2 df) and interaction between floor and batches (2 df). For feed conversions, water intakes, manure characteristics and N-balance, recorded per pen, the differences were tested in the same way but with only floor (1 df) as criterion (proc GLM) (SAS, 2005).

For room temperatures, ventilation rates and gas emissions, the combined data from the 3 batches were tested in the form of a mixed model for repeated measurements (proc MIXED) (SAS, 2005) including the effects of the floor (1 df), the week of measurement (3 df), the interaction between the floor and the week of measurement (3 df) and the batch as random effect (2 df), with 144 (24 h × 6 d) successive measurements per week. Residuals were normally distributed, with a null expectation (proc UNIVARIATE) (SAS, 2005). Correlation between hourly successive measurements was modelled using a type 1-autoregressive structure.

3. Results

3.1. Climatic characteristics of the rooms

The data about the air temperatures and the ventilation rates are shown in Table 2. The slight difference between the treatments can be due to the different thermal leakage of the walls linked to the location of the rooms in the building and the orientation of the building. However, the differences between experimental rooms were not statistically significant (P>0.05). The average temperatures of the air were 19.7 °C in the experimental rooms, 15.5 °C in the service corridor and 8.1 °C outside. The mean ventilation rate was 58 $m^3\ h^{-1}$ per pig.

Table 2 - Climatic characteristics of the experimental rooms

	Batch			
	1[a]	**2**[a]	**3**[a]	**Mean**[b]
Temperatures (°C)				
DL	18.5 ± 1.0	21.3 ± 0.5	20.9 ± 3.3	20.2 ± 1.5
SF	18.1 ± 1.0	19.5 ± 0.7	19.9 ± 3.2	19.1 ± 0.9
Service corridor	12.9 ± 2.3	16.5 ± 1.2	17.1 ± 5.0	15.5 ± 2.3
Outside	0.9 ± 3.5	11.8 ± 3.5	11.8 ± 12.0	8.1 ± 6.3
Ventilation rates ($m^3\ h^{-1}\ pig^{-1}$)				
DL	29.2 ± 17.2	65.1 ± 18.4	67.3 ± 25.7	53.8 ± 21.4
SF	36.5 ± 26.5	66.2 ± 28.0	84.9 ± 32.8	62.5 ± 24.4

DL: room with pigs kept on straw-based Deep Litter; SF: room with pigs kept on Straw Flow; [a] Mean ± standard deviation between the 4 periods of measurements; [b] Mean ± standard deviation between mean values of the 3 batches

3.2. Animal performance

Pig performance and some parameters of carcass quality are presented in Table 3. Whatever the parameter studied, the floor type did not influence significantly animal performance. The mean initial and final body weight was respectively 23 kg and 113 kg with an average body weight gain of 90 kg for a 118 d fattening period and with a mean feed conversion ratio of 3.0. Mean lean meat percentage and mean value of carcasses were 59%.

3.3. Amounts and composition of manure

Table 4 presents the manure characteristics. The differences between manure from DL room and total manure from SF room were statistically not significant for all parameters. There were 43.1 g N and 17.8 g $NH_4^+\ kg^{-1}$ DM of manure. The small number of replicates (3) and the large variation between replicates can partly explain the absence of significance.

Table 3 - Animal performance as influenced by the floor type (straw-based deep litter, DL, or Straw Flow , SF) in fattening pigs (mean ± standard deviation between the 3 batches)

	DL	SF	Significance		
			Batch	Floor	B x F
Number of pigs	48	48	-	-	-
Number of loss	1	0	-	-	-
Initial body weight (kg)	23.3 ± 1.5	23.3 ± 1.4	***	NS	NS
Final body weight (kg)	113.5 ± 5.1	113.0 ± 4.9	NS	NS	NS
Average daily weight gain (g pig^{-1})	760 ± 42	758 ± 45	*	NS	*
Feed intake (kg pig^{-1} d^{-1})	2.32 ± 0.07	2.24 ± 0.05	-	NS	-
Feed conversion ratio	3.05 ± 0.24	2.96 ± 0.12	-	NS	-
Water intake					
L $pig^{-1}d^{-1}$	4.84 ± 0.19	4.50 ± 0.09	-	*	-
L kg^{-1} feed	2.09 ± 0.12	2.01 ± 0.05	-	NS	-
Lean meat percentage (%)	59.0 ± 1.1	59.0 ± 1.7	NS	NS	*

Probability of significance: NS: P>0.05; *: P < 0.05; **: P < 0.01; ***: P < 0.001

Table 4 - Manure characteristics as influenced by the floor type -straw-based deep litter (DL) or Straw Flow (SF)- in fattening pigs (mean ± standard deviation between the 3 batches)

	DL	SF			Sign.
		Total	Solid manure	Liquid manure	Floor
Removed amount (kg pig^{-1})	204.8 ± 61.2	261.6 ± 21.2	208.8 ± 12.5	52.8 ± 8.8	NS
Dry matter (%)	30.9 ± 8.4	21.1 ± 2.4	25.9 ± 2.6	1.6 ± 0.4	NS
Organic matter (%)	25.8 ± 7.2	17.3 ± 2.2	21.5 ± 2.4	0.5 ± 0.3	NS
C/N	10.7 ± 0.6	10.5 ± 1.8	11.9 ± 2.3	0.5 ± 0.3	NS
pH	8.64 ± 0.19	8.47 ± 0.15	8.46 ± 0.09	8.51 ± 0.36	NS
Total nitrogen					
g N kg^{-1}	13.3 ± 3.3	8.84 ± 0.56	9.70 ± 0.87	5.53 ± 1.60	NS
g N kg^{-1} dry matter	43.7 ± 2.2	42.5 ± 7.7	37.9 ± 7.4	350.8 ± 111.8	NS
kg N pig^{-1}	2.60 ± 0.16	2.32 ± 0.31	2.03 ± 0.29	0.30 ± 0.07	NS
Ammoniacal nitrogen					
g N-NH_4^+ kg^{-1}	5.49 ± 3.44	3.76 ± 1.75	3.50 ± 1.82	4.83 ± 1.63	NS
g N-NH_4^+ kg^{-1} dry matter	17.7 ± 8.4	17.9 ± 8.1	13.6 ± 6.9	307.4 ± 114.6	NS
kg N-NH_4^+ pig^{-1}	1.05 ± 0.51	0.98 ± 0.44	0.73 ± 0.37	0.25 ± 0.07	NS

Sign.: Probability of significance: NS: *P*>0.05 (the data taken into account for the straw-flow was the total values)

3.4. Gas emissions

Table 5 presents the overall means of gas emissions and Figure 2 shows the mean evolution of the gas emissions from the beginning to the end of the stay. Fattening pigs on deep litter rather than on straw-flow decreased NH_3-emissions by 9% (P<0.05) and increased N_2O-emissions by 121% (P<0.001), CH_4-emissions by 85% (P<0.001), CO_2eq-emissions by 90% (P<0.001), CO_2-emissions by 11% (P<0.001) and H_2O-emissions by 30% (P<0.001).

For NH_3, CO_2 and H_2O, the emissions increased throughout the pigs' stay in DL and SF groups. N_2O-emissions from the deep litter pens greatly increased between the first and the second measuring periods (5-fold) and then, plateaued around 2 g d^{-1} pig^{-1}. With straw flow, N_2O-emissions increased regularly throughout the four periods of measurements from 0.17 to 1.32 g d^{-1} per pig. CH_4-emissions increased continually throughout the fattening period with DL pigs (from 7.2 to 25.1 g d^{-1} per pig) while, emissions remained quite stable with SF pigs around 9 g d^{-1} per pig.

Table 5 - Gas emissions as influenced by the floor type -straw-based deep litter (DL) or Straw Flow (SF)- in fattening pigs (mean ± standard deviation between the 3 batches)

	d^{-1} pig^{-1}	d^{-1} LU^{-1}	Significance
NH_3 (g)			
DL	12.1 ± 0.6	88.6 ± 4.6	*
SF	13.3 ± 3.4	97.5 ± 25.3	
N_2O (g)			
DL	1.50 ± 1.15	10.96 ± 8.43	***
SF	0.68 ± 0.67	4.98 ± 4.93	
CH_4 (g)			
DL	16.5 ± 1.0	121.1 ± 7.4	***
SF	8.9 ± 1.2	65.2 ± 8.8	
CO_2eq (kg)			
DL	0.91 ± 0.35	6.64 ± 2.59	***
SF	0.48 ± 0.22	3.49 ± 1.63	
CO_2 (kg)			
DL	1.97 ± 0.08	14.46 ± 0.62	***
SF	1.77 ± 0.11	12.99 ± 0.77	
H_2O (kg)			
DL	3.82 ± 0.43	27.97 ± 3.11	***
SF	2.94 ± 0.22	21.5 ± 1.63	

LU: livestock unit, equal to 500 kg body weight;
Significance: *: P<0.5; ***: P<0.001

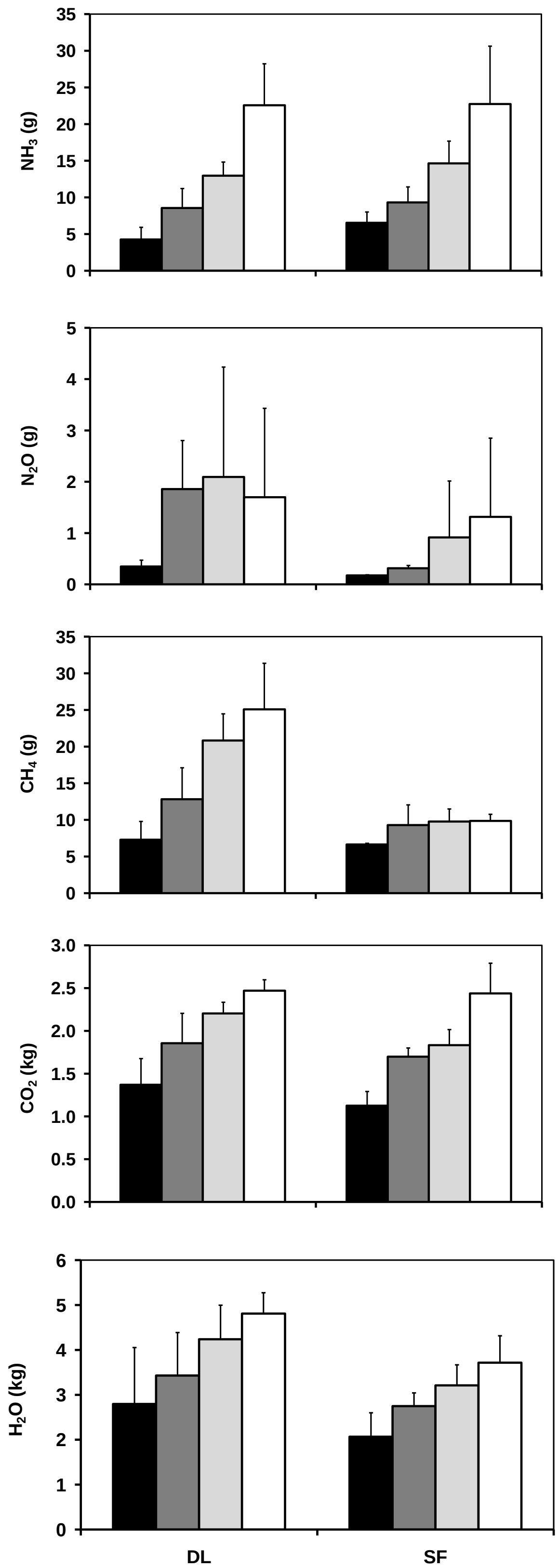


Figure 2 - Gas emissions per day and per pig (mean ± standard deviation between the 3 batches) as influenced by the floor type -straw-based Deep Litter (DL) or Straw Flow (SF)- in fattening pigs according to the stay week (black, dark-grey, light-grey and white bars for weeks 3, 7, 11 and 15 respectively)

3.5. Nitrogen balance

There is no significant difference between the two groups for the N-balance (Table 6). Nitrogen retained by the pigs corresponds to about 30% of the N-feed for both groups, i.e. 18.9 g N d^{-1} pig^{-1}. This is close to the value for N-manure with about 20 g N d^{-1} pig^{-1}, corresponding to almost the half of the excreted N. Nitrogen from NH_3 emissions corresponds to about 24% of excreted-N while fraction from N_2O emissions is quite negligible. Unaccounted N equals 12.1 g N d^{-1} pig^{-1} whatever the floor type. This figure can be partly associated with N_2 and NO emissions. Leached nitrogen and the measurement error may also contribute to this value.

Table 6 - Nitrogen balance (g N d^{-1} pig^{-1})

	DL	SF	Significance
N-inputs			
N-straw (estimated)	2.4 ± 0.0	1.8 ± 0.0	***
N-feed	61.5 ± 1.8	59.5 ± 1.4	NS
N-retention (estimated)	18.9 ± 0.9	18.9 ± 1.3	NS
N-outputs			
N-manure	22.0 ± 1.6 (49%)	18.9 ± 3.7 (44%)	NS
N-NH_3	10.0 ± 0.5(22%)	11.0 ± 2.8 (26%)	NS
N-N_2O	1.0 ± 0.7 (2%)	0.4 ± 0.4 (1%)	NS
Unaccounted N (estimated)	12.1 ± 3.5 (27%)	12.1 ± 5.9 (29%)	NS

Significance: NS: $P>0.05$; ***: $P<0.001$

4. Discussion

Ammonia emission factors reported in the literature for fattening pigs on litter show large variations according to the study. Groot Koerkamp *et al.* (1998) presented values of 2.6 and 9.5 g NH_3 d^{-1} pig^{-1} for England and Denmark, respectively. Nicks *et al.* (2004) obtained NH_3 emissions of 13.6 g d^{-1} pig^{-1} during the fattening of three successive batches on the same straw litter. Balsdon *et al.* (2000) observed higher emissions close to 30 g d^{-1} pig^{-1} for growing/finishing pigs on deep litter. According to the EMEP/EEA guidelines for emission inventories (EMEP/EEA, 2010), NH_3-emissions from buildings for fattening pigs kept on litter can be estimated to 27% of the excreted N, what is slightly higher than data obtained here. Ammonia emissions from sawdust-based deep litter seem to be lower than from straw-based deep litter. Indeed, during the raising of five successive batches of weaned piglets on the same litter, Nicks et al. (2003) obtained reduced emissions with sawdust- compared to straw-based litter (0.46 g vs. 1.21 g NH_3 pig^{-p} day^{-d}). With fattening pigs kept on sawdust litter, emissions of 10 g NH_3 pig^{-1} day^{-1} were measured by Dourmad et al. (2009). Anyway, the emissions measured in the current study with the deep litter are within the range of data from the literature.

With straw-flow systems, Amon *et al.* (2007) reported emissions around 6.5 g NH_3 d^{-1} pig^{-1} and Hornig *et al.* (2001) found emission rates from 7.2 to 11.5 g NH_3 d^{-1} pig^{-1}. NH_3-emissions observed in the current experiment were slightly higher, with a mean value of 13.3 g d^{-1} pig^{-1}. Contrarily to the cited studies, the solid fraction of manure was stored inside the experimental room and thus contributes to emissions.

Usually, frequent manure removal and/or separation of the solid and liquid fractions of manure reduce the NH_3 emissions. With fattening pigs kept on slatted floor, 50% reductions were achieved by the installation of under-slat V-shaped scrapers (Lachance, 2005; Landrain *et al.*, 2009). A litter system with weekly manure removal and straw supplies was associated with low emission around 6 g NH_3 d^{-1} pig^{-1} (Kavolelis, 2006). On the contrary, in the experiment of Amon *et al.* (2007) with straw-flow systems, daily scraping failed to significantly decrease emissions compared to a dung channel system. In the present study, the NH_3 emissions are higher with the SF compared to the DL despite the storage of the liquid fraction in a hermetic tank.

NH_3 emissions come principally from the microbial degradation of urea by enzyme urease, which is abundant in faeces (Muck and Steenhuis, 1981). Former experiments concluded that the urease activity on a concrete floor is rapid and important, with the volatilisation peak occurring 2 to 3 h after application of urine samples (Elzing and Monteny, 1997; Braam and Swierstra, 1999; Groenestein *et al.*, 2007). In the current experiment, the separation of the liquid fraction of the manure from the scraping passage does not prevent rapid NH_3 synthesis from the soiled surface of the pen. Moreover, daily manipulation in scraping solid manure may have favoured NH_3 emissions by aeration, as described by Gibbs *et al.* (2002). Furthermore, the amounts of supplied straw influence the NH_3-emission process. Indeed, more straw (like in DL room) increases the C/N ratio of the litter which favours bacterial growth and promotes the N assimilation into stable microbial protein with lower NH_3-emissions as a consequence (Gilhespy *et al.*, 2009; Philippe *et al.*, 2011b). However, according to Rigolot *et al.* (2010), there is no effect of the amount of bedding material between supplies of 30 and 100 kg straw per fattening pig. For these authors, the surface of the bedded area also influences the microbial process in the litter. Thus, larger area is associated to reduced NH_3 emissions due to promotion of complete nitrification/denitrification reactions and the consequent higher N_2 emissions. This is in agreement with the results obtained in this experiment (lower NH_3 emissions related to the system with the larger area, i.e. the DL system), but this is in opposition with the findings of Philippe et al. (2010) who obtained higher NH_3 emissions (+17%) by increasing the bedded area of gestating sows (+20%) with the same amount of straw.

The formation of N_2O occurs during incomplete nitrification/ denitrification processes that normally convert NH_4^+ into dinitrogen, a non-polluting gas. 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). Therefore, its formation needs both aerobic and anaerobic conditions. These heterogeneous conditions can be found in deep litter or manure heaps (Veeken *et al.*, 2002).

For piggeries with deep litter systems, most of values reported in literature range from 1 to 10 g N_2O d^{-1} pig^{-1} (Groenestein and Van Faassen, 1996; Robin *et al.*, 1999; Hassouna *et al.*, 2005; Philippe *et al.*, 2006a; Dourmad et al., 2009). Hassouna et al. (2005) reported emissions factors in the range of 4-12 % of the excreted N for available space area lower than 2 m^2 per pig. Litter based on sawdust seems to be associated to higher emissions than ones based on straw (Nicks et al., 2003; Cabaraux et al., 2009; Rigolot et al., 2010). By example, Nicks et al. (2003) presented emissions of 0.36 and 1.39 g N_2O d^{-1} for weaned pigs kept on straw- and sawdust-based litter, respectively. IPCC guidelines for national inventories (IPCC, 2006) present emission factors for pigs on litter: cumulated N_2O emissions from buildings and manure storage can be estimated to 1% of excreted N. This is close to the value obtained with the SF system (1% of excreted N or 0.68 g N_2O d^{-1} pig^{-1}) but lower than the value obtained with the DL systems (2% of excreted N or 1.50 g N_2O d^{-1} pig^{-1}), only from the buildings. With sloped floor, Amon *et al.* (2007) obtained an average daily emission of 0.07 g N_2O d^{-1} pig^{-1}.

In the current experiment, the N_2O-emissions were low in both rooms during the first week of measurement, corresponding to the 4^{th} week of stay. Thereafter, emissions increased regularly in the SF room and reached a plateau around 2 g N_2O d^{-1} pig^{-1} in the DL room. During the storage of manure heaps, some authors found that N_2O production increased only 1 month after the storage began (Sommer and Moller, 2000; Hansen et al., 2006). Indeed, at the beginning of the storage, low litter density associated to thermophilic conditions could prevent the N_2O production by nitrifying/denitrifying bacteria. It could be the case with the DL system during the first weeks of fattening. Thereafter, dejections accumulate in some part of the litter creating more anaerobic areas close to aerobic areas, with higher N_2O-emissions as consequence. By contrast, with the SF system, the regular removal and the aeration of the manure heap due to the heap's physical structure and the daily manual scraping could explain the lower emissions. The regular increase of emissions in the SF room was probably due to the greater amount of emitted dejections in one week by the pigs at the end than at the beginning of the fattening. The effect of the surface of the bedded area on N_2O-emissions was studied by several authors with typically reduced emission with the larger available space (Hassouna et al., 2005; Philippe et al., 2010; Rigolot et al., 2010). By example, for gestating sows, an increase of the available space from 2.5 to 3.0 m^2 per animal is associated to a decrease of the emissions from 3.9 to 2.8 g N_2O d^{-1} sow^{-1} (Philippe et al., 2010). These results are in contrast with the current experiment where the higher N_2O emissions were measured in the pen with the higher space area (DL system). However, the two systems differ not only by the surface area but by many other factors like the amount of straw and the litter management that also impact the N_2O production.

Few data are available concerning CH_4-emissions with fattening pigs on deep litter. Stout *et al.* (2003) reported a mean emission of 2.77 g CH_4 d^{-1} $pig^{-1}$and Nicks *et al.* (2004) obtained on average 7.39 g CH_4 d^{-1} pig^{-1} during the fattening of three successive batches of pigs on the same straw-based deep litter. With the straw-flow system, results in the literature ranged from 1.5 (Amon *et al.*, 2007) to 20 g CH_4 d^{-1} pig^{-1} (Hornig *et al.*, 2001). With sawdust-based litter for fattening pigs, Dourmad et al. (2009) obtained 5.9 g CH_4 d^{-1} pig^{-1}. Comparisons between straw- and sawdust-based litter shown lower emissions from the latter (Nicks et al., 2003; Cabaraux et al., 2009).

Methane originates from anaerobic degradation of organic matter (Hellmann *et al.*, 1997). Methanogenesis is mainly performed by mesophilic bacteria (25–40 °C) with an optimal pH close to neutrality (El-Mashad *et al.*, 2004). In piggery, the two main sources of CH_4-emissions are the animal digestive tract and the waste.

Enteric CH_4 is estimated to 0.4% of the digestible energy according to a review of Le Goff (2001), and to 1.2% of the ingested digestible residue according to Vermorel et al. (2008). It corresponds to about 2-3 g CH_4 d^{-1} pig^{-1}. Actually, 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 the current experiment, these parameters are assumed to be identical for the two groups. Therefore, the difference comes principally from the manure characteristics.

In manure, CH_4-release is promoted by high temperature, high organic matter content and anaerobic conditions (Amon *et al.*, 2006; Haeussermann *et al.*, 2006). On one hand, straw supply may inhibit production because of greater manure aeration. On the other hand, straw may enhance CH_4-emissions by providing degradable carbohydrates that initiate and maintain the microbial activity (Amon *et al.*, 2006; Yamulki, 2006).In the first stages of decomposition process, easy degradable substrates are converted by unspecified microbial community, with rapid increase of the temperature as consequence. Thereafter, the increase of anaerobicity with the course of time combined with elevate temperature provide suitable conditions for CH_4-producing bacteria (Hellmann et al., 1997). These elements could explain the regular increase of the CH_4-emissions in the DL room with the accumulation of dejections. Contrarily, in the SF room, the daily scraping, the manure heap aeration and the shorter storage duration could explain the reduced emissions.

As N_2O- and CH_4-emissions were lower in the SF room, CO_{2eq}-emissions were consequently lower in this room. In DL room, about 910 g CO_{2eq} d^{-1} were emitted per pig, 46% coming from CH_4-emissions, 49% from direct N_2O-emissions and 5% from indirect N_2O-emissions. The corresponding values from the SF room were respectively 47%, 42% and 11% with total CO_{2eq}-emissions of about 480 g d^{-1} pig^{-1}.

The CO_2-production from piggeries originates mainly from animal respiration but also from manure releases. CO_2-exhalation by pigs is function of energy metabolism and thus of body weight, feed intake and animal activity (CIGR, 2002; Pedersen *et al.*, 2008). In the present trial, as the two groups had the same body weight, the same performance and the same surroundings, CO_2-exhalation was considered similar in the 2 rooms and was estimated to be about 1.5 to 1.7 kg d^{-1} for a 65-kg pig (Ni *et al.*, 1999; CIGR, 2002).

In the manure, the formation of CO_2 comes from (1) the rapid hydrolysis of urea into NH_3 and CO_2, (2) the anaerobic fermentation of manure, but mainly (3) the aerobic degradation of organic material, namely composting process (Jeppsson, 2000, Moller *et al.*, 2004; Wolter *et al.*, 2004). The rate of composting is influenced by degradability of organic matter, temperature, moisture content, C/N ratio, pH level and oxygen level (Jeppsson, 2000). In the current experiment, the CO_2 manure production can be estimated by subtracting calculated animal emissions from total measured emissions. It corresponds to about 370 g and 170 g d^{-1} pig^{-1} from DL and SF rooms, respectively, or to about 10-20% of whole emissions, in accordance with the results of Jeppsson (2000). As seen the importance of CO_2 emission in the estimation of ventilation rate, particularly for naturally ventilated buildings, these results confirmed that CO_2 from manure cannot be neglected, especially in litter systems.

Like CH_4 and CO_2, H_2O-emissions have two origins: animals and manure. Evaporation by animals is function of body weight, heat production and ambient temperature (CIGR, 2002). Evaporation from manure is relatively important and function of litter temperature related to the level of the microbial fermentation. With straw-based deep litter, some authors have presented emissions ranging from 2.7 to 5.2 kg H_2O d^{-1} pig^{-1} (Robin *et al.*, 1999; Jeppsson, 2000; Nicks *et al.*, 2004). The CIGR (2002) estimated H_2O production at house level to be about 2.7 kg per day for a 65-kg pig kept on partly slatted floor with a room temperature of 20.5°C. De Oliveira *et al.* (1999) reported that the emission rate from slurry was negligible. Therefore, with the slatted-floor system, emissions at house level can be considered to come quasi- exclusively from animals. The lower H_2O-release from the SF system could be explained by the storage of the liquid manure in a hermetic tank and the removing of the manure heap 1 week before measurements. Moreover, with the DL system, there was an increase in litter temperature with time due to fermentation that promotes evaporation.

5. Conclusion

In the current experiment with fattening pigs kept either on straw based deep litter or straw flow system, the animal performance and the manure characteristics were not greatly influenced by the floor type. About the emission of pollutant gases, significant differences were observed between treatments. The straw flow system is associated with increased NH_3-emissions (+10%) but reduced GHG-emissions (-55%, -46% and -10% for N_2O, CH_4 and CO_2 respectively). As seen the relative contribution of pig production to global emissions, techniques that increases NH_3 emissions, have significant impact on global scale. At the opposite, techniques that mitigate the GHG emissions from pig production have globally less impact. Anyway, entire assessment of the technique has to integrate the complete process including manure storage and spreading. Finally, this study showed that litter management (amount of substrate, frequency of supply, removal strategy ...) greatly affect the emissions and stressed the need for more specific values for each type of bedded system.

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6. EMISSIONS D'AMMONIAC ET DE GAZ A EFFET DE SERRE ASSOCIEES A L'ELEVAGE EN GROUPE DE TRUIES GESTANTES SUR LITIERE DE PAILLE ACCUMULEE AVEC ACCES OU NON A UNE SURFACE BETONNEE

La technique d'hébergement sur litière regroupe un grand nombre de modalités différentes en fonction du mode de gestion de l'effluent. Dans les études précédentes, il a été observé que ces différentes adaptations du système pouvaient influencer la production des gaz polluants. La conformation des loges peut également avoir un impact sur les niveaux d'émissions. Ainsi, certains modes de logement combinent plusieurs types de sol (litière, caillebotis et/ou sol bétonné) afin de favoriser la séparation par les animaux des comportements de repos, d'alimentation et d'excrétion, avec pour objectif de limiter les émissions polluantes (Aarninck et al., 1996 ; Groenestein et al., 2007). Pour des truies gestantes élevées en groupe, l'utilisation de stalles d'alimentation individuelles avec système de fermeture permet en outre d'empêcher la compétition alimentaire au moment des repas, en accord avec la Directive 2001/88/CE. En dehors des repas, l'accès au réfectoire peut être autorisé ou non, ce qui modifie le besoin en surface nécessaire pour garantir un espace disponible suffisant aux animaux. Le réfectoire étant généralement disposé sur un sol bétonné, cela modifie également le type de sol disponible, avec des répercussions possibles sur les émissions gazeuses. L'objectif de cette étude était donc d'évaluer l'impact de l'accès permanent à des stalles d'alimentation sur sol bétonné sur les émissions de NH_3, N_2O, CH_4 et CO_2 pour des truies gestantes élevées en groupe sur litière de paille accumulée.

Deux locaux expérimentaux, similaires en volume (103 m^3) et en surface (30 m^2), ont chacun été équipés d'une loge permettant d'héberger un groupe de 5 truies gestantes. Les loges étaient composées d'une zone paillée à laquelle était accolée une zone bétonnée sur laquelle étaient disposées cinq stalles individuelles d'alimentation (1,2 m^2 par truie). Un dispositif de fermeture équipait les stalles permettant de maintenir les truies à l'intérieur durant les repas. En dehors des repas, l'accès au réfectoire était empêché dans une loge (sol entièrement paillé) et laissé libre dans l'autre loge (sol partiellement paillé). La surface de la zone paillée était de 15 m^2 (3,0 m^2 par truie) et 9 m^2 (1,8 m^2 par truie) respectivement dans ces deux loges. La surface totale disponible était donc de 3 m^2 par truie dans chacune des loges. La quantité initiale de paille était de

135 kg dans les deux loges. A intervalles réguliers, des apports supplémentaires de paille ont été réalisés simultanément et en quantités identiques dans les deux locaux pour atteindre en fin de gestation un paillage équivalent à 0,90 kg truie^{-1} jour^{-1}. Trois bandes successives de 10 truies gestantes de race Landrace belge, réparties uniformément en deux groupes en fonction de la parité, du poids et de l'épaisseur de lard dorsal, ont été hébergées dans les locaux depuis la 6ème semaine de gestation jusqu'à 7 jours avant la date prévue de mise-bas. Après le départ de chaque bande de truies, les fumiers étaient évacués et les loges nettoyées. La ventilation des locaux se faisait de manière contrôlée avec adaptation automatique du débit de ventilation en fonction de la température, (Fancom, Panningen, Pays-Bas). Les concentrations en gaz ont été mesurées dans les locaux expérimentaux et dans le couloir d'apport d'air par moniteur photo-acoustique infrarouge équipé pour la mesure simultanée de NH_3, N_2O, CH_4, CO_2 et H_2O (1312 Photoacoustic Multi-Gas Monitor, Innova Air Tech Instruments, Nærum, Denmark). Trois séries de mesures de six jours consécutifs réparties sur la période de gestation ont été réalisées pour chaque bande de truies. Les émissions (E_{gaz}) ont été calculées sur base horaire grâce à l'équation suivante :

$E_{gaz} = D \times (C_i - C_e)$,

avec D, le débit de ventilation (kg air h^{-1}), et C_i et C_e, respectivement la concentration en gaz dans l'air du local expérimental et du couloir d'apport d'air (mg kg^{-1} air). Les résultats d'émissions ont été testés au moyen d'un modèle mixte pour données répétées (SAS, Mixed Proc) en incluant l'effet du type de sol (1 dl), de la série de mesure (2 dl) et de l'interaction sol-série (2 dl) avec 144 données (24 heures x 6 jours) par série de mesure.

Les émissions de NH_3 n'ont pas été significativement différentes entre les deux loges, avec en moyenne 7,9 g NH_3 truie^{-1} jour^{-1} ($P>0,05$). Les études précédentes nous ont montré d'une part que la production de NH_3 était proportionnelle à surface paillée (Philippe et al., 2010) et que d'autre part, la présence de déjections sur un sol bétonné pouvait être une source importante d'émissions (Philippe et al., 2012). Dans la présente étude, il semblerait que les deux phénomènes se soient compensés. Avec le système partiellement paillé, les émissions potentielles dues à la souillure du réfectoire en sol bétonné ont été contrebalancées par la réduction de la surface d'émission de la litière.

Les émissions de N_2O ont été plus élevées à partir de la loge ayant la plus grande zone paillée (6,12 *versus* 3,14 g N_2O truie^{-1} jour^{-1}, $P<0,001$). Ce résultat est contraire à ce qui avait été observé dans l'étude portant sur l'effet de la taille de la surface paillée (Philippe et al., 2010) où les émissions étaient plus basses avec une surface paillée plus grande. La synthèse de N_2O nécessite la présence dans la litière de zones aérobies finement associées à des zones anaérobies (Poth et Focht, 1985). Si une porosité plus élevée des fumiers limite la production de N_2O (Kermarrec et Robin et al., 2002), il semblerait également qu'un tassement trop important de la litière en diminue les émissions. En effet, des analyses comportementales effectuées durant cette étude ont montré une préférence des truies pour occuper la partie paillée comme zone de couchage au détriment de la zone bétonnée, avec comme conséquence une plus grande compaction de la litière. Cela montre l'influence que peuvent avoir des paramètres comportementaux sur les émissions de gaz polluants.

Les émissions de CH_4 ont été plus élevées dans la loge partiellement paillée (12,76 *versus* 9,90 g CH_4 truie^{-1} jour^{-1}, $P<0,001$). La production digestive, calculée à partir des ingestions de fibres, est estimée identique pour les deux types de logement, avec environ 8 g truie^{-1} jour^{-1} (Philippe et al., 2008). Le tassement plus important de la litière dans la loge partiellement paillée semble être le facteur responsable du niveau d'émission plus élevé, la méthanogenèse étant un phénomène anaérobie.

Les émissions de CO_2 ont été plus importantes en cas d'accès permanent à la zone bétonnée (3,12 *versus* 2,90 kg CO_2 truie^{-1} jour^{-1}, $P<0,01$). En estimant la production de CO_2 respiratoire à partir du poids corporel et des ingestions alimentaires (CIGR, 2002), on obtient une valeur de 2,8 kg CO_2 truie^{-1} jour^{-1} pour les deux types de logement. La différence d'émission globale pourrait s'expliquer par des niveaux de production différents au niveau des fumiers. Dans l'effluent, le CO_2 peut avoir pour origine l'hydrolyse rapide de l'urée et la dégradation de la matière organique en conditions aérobie ou anaérobie (Moller et al., 2004 ; Wolter et al., 2004). L'importance relative de ces différentes voies de synthèse dépend des propriétés physico-chimiques des effluents (Jeppsson, 2000). L'environnement particulier rencontré dans les litières semble donc avoir favorisé les émissions à partir du système partiellement paillé.

En conclusion, l'accès permanent à la zone bétonnée d'alimentation pour des truies en groupe logées sur paille n'a pas modifié le niveau d'émission de NH_3 mais a impacté la production de GES (réduction des émissions de N_2O et augmentation des émissions de CH_4 et CO_2) en raison de conditions particulières rencontrées dans les litières, comme par exemple un taux de compaction plus important dû au comportement des animaux.

Influence of permanent use of feeding stalls as living area on ammonia and greenhouse gas emissions for group-housed gestating sows kept on straw deep-litter

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Abstract

In pig production, the interest for litter systems in relation with animal welfare and the ban by 2013 in the EU of individual accommodations for gestating sows could promote the group-housing of gestating sows on deep-litter. However, compared to slatted-floor systems, few data are available on the gaseous emissions associated with the different modalities of rearing sows on deep-litter. In this study, two modalities were compared: group housing on a 3 m^2/sow deep-litter or on a 1.8 m^2/sow deep-litter plus 1.2 m^2/sow concrete floor. In both cases, sows were fed in individual feeding stalls (1.2 m^2/stall) but the access was limited at feeding time in the first case and permanent in the second one. Three successive batches of 10 gestating sows were used. Each batch was divided into 2 homogeneous groups randomly allocated to one of two treatments: fully (3 m^2/sow) or partly (1.8 m^2/sow) straw-based deep-bedded floor. The groups were kept separately in two identical rooms with same volume and same surface, equipped with five individual feeding stalls in contact with a pen of either 9 or 15 m^2 deep-litter. The feeding stalls were equipped with front feeding troughs and rear gates allowing or not permanent access to the stalls outside of feeding times. Between each batch, the pens were cleaned.

In both rooms, ventilation was automatically adapted to maintain a constant ambient temperature. The gas emissions (nitrous oxide, methane, carbon dioxide, ammonia and water vapour) were measured 3 times (weeks 2, 5 and 8 of stay) during 6 consecutive days by infrared photoacoustic detection.

Sow performance was not significantly affected by floor type. With sows kept on partly bedded floor, gaseous emissions were significantly greater for methane (12.76 *vs.* 9.90 g/d.sow; $P<0.001$), carbon dioxide (3.12 *vs.* 2.90 kg/d.sow; $P<0.01$) and water vapour (4.70 *vs.* 4.03 kg/d.sow; $P<0.001$), and significantly lower for nitrous oxide (3.14 *vs.* 6.12 g/d.sow; $P<0.001$) and CO_2 equivalents (1.24 *vs.* 2.10 kg/d.sow; $P<0.001$) compared to sows housed on fully bedded floor. There was no significant difference for ammonia emissions (8.36 *vs.* 7.45 g/d.sow; $P>0.05$).

From the present trial in experimental rooms, it can be concluded that keeping group-housed gestating sows on partly straw bedded floor with permanent access to the concrete feeding stalls compared to fully straw bedded floor did not significantly influence animal performance and NH_3-emissions, and decreased CO_2eq-emissions (-40%). This decrease was observed owing to an important decrease of N_2O-emissions (-49%).

1. Introduction

Compared with slatted-floor systems, litter systems in pig production present advantages in terms of animal welfare improvements (Tuyttens, 2005), odour nuisance reduction (Kaufmann, 1997) and a better perception by the consumers and the neighbours (Chevrant-Breton and Daridan, 2003). Litter systems are however associated with increased production costs related to the use of straw and to the labour for litter management (Nicks, 2004). Furthermore, gaseous emissions from deep litter systems have been little studied compared with slatted-floor systems.

Whatever the floor type, the EU legislation imposes, by 2013, to keep gestating sows in groups from at least 4 weeks after insemination until 1 week before farrowing with a minimum floor area per sow of 2.25 m^2 ± 10% according to the size of the group (Directive 2001/88/CE). The directive also specifies that group-housed sows have to be fed using a system which ensures that each individual can obtain sufficient feed even when competitors for the feed are present. One option to satisfy this rule is the use of individual feeding stalls with rear gates allowing sows to be undisturbed during the feeding times. Outside of feeding times, if the rear gates are continually kept open, the permanent access to these feeding stalls can thus be considered as living area. Taking into account this area for calculating the legal available surface is debated in some countries. Compared with a system where the rear gates of feeding stalls would be continually kept closed outside of feeding times, this system allows reducing the construction or renovation costs of pig buildings (due to the reduced need for surface area).

If a permanent access to the feeding stalls is associated with a deep litter system, the living area of the sows can be considered as a partly bedded floor subdivided into a deep litter floor and a concrete floor. This subdivision could influence sows performance and environmental parameters such as gaseous emissions (ammonia (NH_3) and greenhouse gases (GHG)).

NH_3-emissions contribute to soil and water acidification and eutrophication and to indirect emissions of nitrous oxide (N_2O) (Intergovernmental Panel on Climate Change (IPCC), 2006). Furthermore, NH_3 is a well-known toxic gas, irritating the respiratory tract at concentrations exceeding 15 ppm (Banhazi *et al.*, 2008). According to Reidy *et al.* (2009), more than 80% of the total NH_3 emissions come from agriculture. In Europe, pig production represents nearby 25% of the livestock emissions (European Environment Agency, 2010). Releases from buildings are the main source, accounting for about 50% of pig NH_3 (Philippe *et al.*, 2011)

The GHG associated with livestock production are carbon dioxide (CO_2), methane (CH_4) and N_2O. Among these gases, N_2O also contributes to the destruction of the ozone layer. N_2O and CH_4 are important contributors because their global warming potential (GWP) over a 100-year period are 298 and 25 times that of CO_2 (IPCC, 2007), respectively. For CO_2, it is assumed that emissions due to feed utilization by animals are compensated by consumption by photosynthesis of plants used as feed (IPCC, 2007). However, CO_2 as well as H_2O emissions in the building may differ between rearing systems as shown by example for weaning and fattening pigs (Philippe *et al.*, 2007a, b; Cabaraux *et al.*, 2009). Besides, CO_2 and H_2O emissions are key parameters in specifying ventilation rates in order to avoid excessive concentrations in livestock buildings, especially for water vapour with bedded systems (CIGR, 2002; Banhazi *et al.*, 2008).

Therefore, the aim of this study was thus to evaluate the impact of a partly bedded floor for group-housed gestating sows on gaseous emissions (NH_3, N_2O, CH_4, CO_2 and H_2O) compared to fully bedded floor.

2. Material and methods

The trial was carried out in experimental rooms located at the Faculty of Veterinary Medicine of Liège University (Belgium). The ethical committee of the university approved the use and treatment of animals in this study.

2.1 Experimental rooms

Two experimental rooms, similar in volume (103 m^3) and surface (30.2 m^2), were arranged for this experiment. Rooms consisted of a service area and a pen designed to group-house five gestating sows on deep-litter either on a partly bedded floor (PBF) or on a fully bedded floor (FBF). In PBF room, the pen consisted of a straw-bedded area (9.0 m^2, i.e. 1.8 m^2 per sow) and five individual feeding stalls (1.2 m^2 per stall, Figure 1). The feeding stalls were raised to a height of 30 cm and were equipped with front feeding troughs and rear gates. The sows had permanent access to the stalls. The total available area was thus 3.0 m^2 per sow. In FBF room, the pen plan was alike but the bedded area was of 15 m^2 (i.e. 3.0 m^2 per sow) and the sows had access to the feeding stalls only during the feeding times (1 h a day). There was a water trough with *ad libitum* access in each pen. Just before the arrival of the animals, about 100 kg of whole wheat straw was used per pen to constitute the initial deep-litter of about 25-30 cm in depth. Thereafter, 25 kg of straw was added once a week per pen and the soil of the feeding stalls was scraped with the droppings pushed towards the bedded area. After each batch, the manure was removed and the pens were cleaned. The manure was weighed and sampled after homogenisation (two samples per room and per batch). The samples were analysed to determine the contents of dry matter, organic matter, total N (Kjeldahl method) and ammonium ions (NH_4^+), using Dutch standard methods for manure and derivatives (Schulten, 1998a, b, c, d). Each room was ventilated with an exhaust fan (Fancom, Panningen, The Netherlands) and the ventilation rate was adapted automatically to maintain a constant ambient temperature (FCTA regulator, Fancom, Panningen, The Netherlands). Fresh air entered through a 0.34 m^2 opening which was connected to the service corridor; the outside air was thereby preheated before entering the experimental rooms. The air temperatures of the experimental rooms, the corridor and the outside were measured automatically every hour. The ventilation rates were measured continuously with an Exavent apparatus (Fancom, Panningen, The Netherlands) with accuracy of 35 m^3/h and a maximal ventilation capacity of 3000 m^3/h as specified by the manufacturer. The hourly means were recorded.

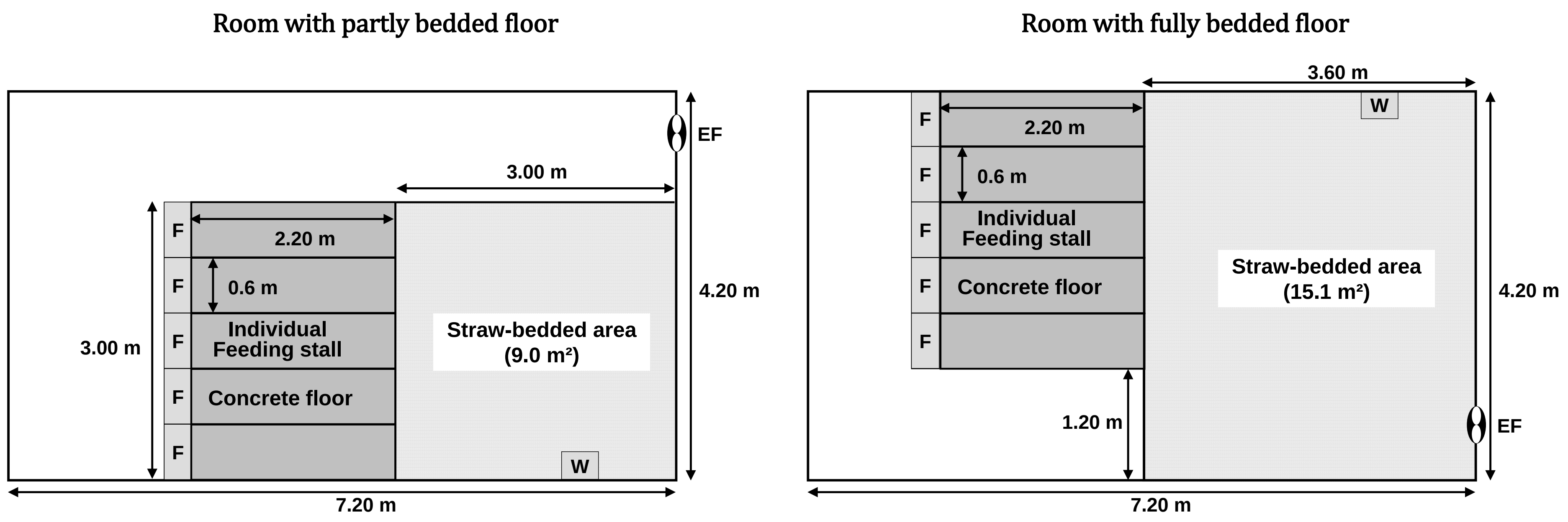

Figure 1- Design of the experimental rooms (F: feeding trough; W: water trough; EF: exhaust fan)

The PBF-room was also equipped with a video camera, allowing seeing the entirety of the pen and the feeding stalls. During 8 days, uniformly spread during the stay, the sows were videotaped during 24 hours to make group observations. Thereafter, these videos were watched and, outside of the feeding times (23 h a day), the number of sows present in the feeding stalls (from 0 to 5) was noted by instantaneous sampling at 10-minute intervals. So, a total of 1104 samplings were analysed per batch (8 days x 23 h/day x 6 samplings/h).

The percentages of stall inoccupation and occupation by only 1 sow or by groups of 2 to 5 sows were calculated and defined as occupation times. An occupation rate taking into account both the time of occupation and the number of sows in the stalls was also calculated on hourly and daily basis, with a 100% value if the 5 sows were observed in the stalls during all the observation time.

2.2. Animals and feed

Three successive batches of 10 Belgian Landrace gestating sows were used. They were divided into 2 groups of 5 animals similar according to the parity, the body weight and backfat thickness. Each group was randomly allocated to a treatment: PBF or FBF. About 5 weeks after service, the gestating sows arrived in the experimental rooms and 7 days prior to expected farrowing, they were moved to farrowing pens; the stay duration was thus 10 weeks for each batch.

The sows received a commercial conventional gestation diet mainly based on cereals (wheat, wheat bran, barley and corn) and contained 9140 kJ net energy per kg diet (Table 1). The amounts of daily feed was restricted and determined per sow as a function of parity and backfat thickness. The feed was supplied once a day at 08:00 AM and all the sows were blocked in the individual feeding stalls during feeding time (1 h).
Individually, the sows were weighed and backfat thickness was measured on P2-site by ultrasonography (Dourmad *et al.*, 2001) at the beginning and at the end of the trial period. The feed and water intakes were recorded per group and per batch. The numbers of piglets born alive and stillborn were recorded.

Table 1 - Composition of diet (as-fed basis)

Ingredient (%)	
Wheat	33.0
Wheat bran	12.5
Barley	11.9
Corn	10.0
Sugar beet pulp	6.7
Rapeseed meal	5.0
Pea	4.6
Palm kernel meal	4.0
Soybean pod and shell	4.0
Sunflower meal	3.9
Minerals-vitamins complex	2.4
Lard	1.7
Linseed oil	0.2
Chemical composition (%)[a]	
Moisture	12.1
Crude protein	12.7
Crude fat	4.1
Crude ash	4.9
Crude cellulose	7.8
Starch	37.2
Sugar	3.4
NSP[b]	25.6
Net Energy (kJ/kg)	9140

[a] Calculated with the InraPorc® program (INRA, 2006); [b]Non-starch polysaccharides, calculated as 100 - (moisture + CP + crude fat + crude ash + starch + sugar)

2.3. Gas emissions measurement

The concentrations of gases in the experimental rooms and in the corridor supplying fresh air were measured by infrared photoacoustic detection with a Photoacoustic Multi-gas Monitor - INNOVA 1312 (LumaSense Technologies A/S, Ballerup, Denmark) equipped for simultaneous measurement of NH_3, N_2O, CH_4, CO_2 and H_2O in accordance with ISO 6142 and ISO 1995. The lower levels of detection were 0.2 ppm for NH_3, 0.03 ppm for N_2O, 0.1 ppm for CH_4 and 3.4 ppm for CO_2, with an accuracy rate of 95%. The monitor was rented for each week of measurements at Enmo Company (Turnhout, Belgium) which calibrated the INNOVA. The air was sampled just upstream of the exhaust fan in the experimental rooms and at 1 m from the air inlets in the corridor. For each batch, the concentrations were measured 3 times (weeks 2, 5 and 8 of stay) during 6 consecutive days. The Multi-gas monitor was programmed by conducting a cycle of 3 measurements every hour, once every 20 min, the air being sampled successively in the 2 experimental rooms and the corridor.

For each gas, the emissions (E_{gas}) were calculated on an hourly basis and expressed in mg/h using the following formula:

[1] $E_{gas} = D \times (C_{in} - C_{out})$

with D, the hourly mass flow (kg air/h); C_{in} and C_{out}, the concentrations of gas in the air of the room and corridor respectively (mg/kg dry air). The mean emissions per day and per sow were calculated for each series of measurements.

The GWP of the GHG, N_2O and CH_4 together, was expressed in CO_2 equivalents (CO_2eq). CO_2 emissions from the building were excluded from this estimation as recommended by IPCC (2006). However, indirect N_2O-emissions from atmospheric deposition of nitrogen (N) from NH_3 on soils and water surfaces have been added to the direct N_2O-emissions. The indirect emissions were calculated considering an emission of 0.01 kg N_2O-N per kg emitted NH_3-N (IPCC, 2006). The emissions of CO_{2eq} (kg/d per sow) were thus calculated using the following equation:

[2] $E_{CO2eq} = 25\ E_{CH4} + 298\ (E_{N2O} + 0.01\ E_{NH3\text{-}N} \times 44/28)$

taking into account that the warming potentials of CH_4 and N_2O over a 100-year period are, 25 and 298 times that of CO_2, respectively (IPCC, 2007). This estimation considered the emissions from the building but not the emissions related to the storage and the spreading.

2.4 Nitrogen balance

Nitrogen balance (g N/d per sow) was calculated for each group with inputs corresponding to N-straw and N-feed and outputs corresponding to N-retention, N in manure and N in gaseous emissions of NH_3 and N_2O. The determination of N-manure, NH_3-N and N_2O-N were described above. N-straw was determined from sample analysis (one sample par batch) by Kjeldahl method. N-feed values were based on diet composition and consumption by sows. N-retention was derived from the difference in protein composition of sow's body ($Prot_{content}$, in kg) between the end and the beginning of the experiment, calculated according to equation proposed by Dourmad *et al.* (2008) based on body weight (BW, in kg) and backfat thickness (BT, in mm):

[3] $Prot_{content}\ (kg) = 2.28 + 0.171\ BW - 0.333\ BT$

Unaccounted-N, as default value, was calculated by the following equation:

[4] Unaccounted-N = (N-straw + N-feed) - (N-manure + N-NH_3 + N-N_2O + N-retention)

2.5. Statistical analyses

For animal performance data recorded per sow, the differences between groups housed on 2 different floors (PBF *vs.* FBF) were tested using analysis of variance with 2 factors (proc GLM) (SAS, 2005): floor (1 df), batches (2 df) and interaction between floor and batches (2 df). For intakes data, manure characteristics and N balance, recorded per pen, the differences were tested in the same way but with only floor (1 df) as factor (proc GLM) (SAS, 2005).

For room temperatures, ventilation rates and gas emissions, the combined data from the 3 batches were tested in the form of a mixed model for repeated measurements (proc MIXED) (SAS, 2005) including the effects of the floor (1 df), the week of measurement (2 df), the interaction between the floor and the week of measurement (2 df) and the batch (2 df), with 144 (24 h × 6 d) successive measurements per week. Residuals were normally distributed, with a null expectation (proc UNIVARIATE) (SAS, 2005). Correlation between successive measurements was modelled using a type 1-autoregressive structure.

3. Results

3.1. Climatic conditions of the rooms

The data about the air temperatures and the ventilation rates are shown in Table 2. The differences between experimental rooms were not statistically significant ($P > 0.05$). In the PBF room, ventilation rates ranged from 176 to 523 m^3/h per sow while air temperatures ranged from 19.1 to 20.9°C. In the FBF room, ventilation rates ranged from 163 to 454 m^3/h per sow while air temperatures ranged from 18.7 to 20.7°C. It reflects the adaptation of ventilation rates according to air temperatures.

3.2. Animal performance

The average staying duration of sows in the experimental unit was 75 days. The performance of sows is presented in Table 3. Whatever the parameter studied, the floor type did not influence significantly animal performance. The mean initial and final body weight were 218.3 kg and 260.7 kg, respectively, with an average body weight gain of 42.4 kg and an average feed intake of 2.74 kg/d. The mean initial and final backfat thicknesses were 17.7 mm and 21.6 mm, respectively, with a backfat thickness gain of 3.9 mm. On average, each sow gave birth to 11.8 piglets of which 10.5 were alive.

Table 2 - Climatic conditions of the experimental rooms (mean ± standard deviation between the 3 periods of measurements)

Climatic conditions	Batch		
	1	2	3
Temperatures (°C)			
PBF	19.1 ± 0.6	17.8 ± 1.3	20.9 ± 1.5
FBF	18.7 ± 0.7	18.1 ± 0.8	20.7 ± 1.6
Service corridor	15.3 ± 1.3	15.3 ± 0.9	19.7 ± 1.5
Outside	4.3 ± 4.6	4.4 ± 1.6	17.6 ± 1.3
Ventilation rates (m^3/h.sow)			
PBF	176 ± 74	309 ± 47	523 ± 80
FBF	163 ± 45	298 ± 39	454 ± 150

PBF: room with sows kept on Partly Bedded Floor; FBF: room with sows kept on Fully Bedded Floor

Table 3 - Animal performance as influenced by floor type -partly bedded floor (PBF) or fully bedded floor (FBF)- in gestating sows (least-square means)

Animal performance	Floor type		SEM	Significance		
	PBF (n=15)	FBF (n=15)		F	B	F x B
Parity	6.4	7.1	0.6	NS	NS	NS
Initial body weight (kg)	215.7	220.9	6.9	NS	NS	NS
Final body weight (kg)	261.1	260.3	6.1	NS	NS	NS
Initial backfat thickness (mm)	17.6	17.8	0.9	NS	NS	NS
Final backfat thickness (mm)	22.0	21.2	1.7	NS	NS	NS
Number of born piglets						
Alive	10.6	10.3	0.7	NS	NS	*
Stillborn	1.6	0.9	0.6	NS	NS	NS
Total	12.2	11.3	1.0	NS	NS	NS
Consumption						
Feed intake (kg/d)	2.74	2.74	0.07	NS	-	-
Water intake (L/d)	6.06	6.11	0.46	NS	-	-

n: Numbre of sows; SEM: Standard error of the means; F: Floor type; B: Batch
Significance: NS: $P>0.05$; *: $P<0.05$

3.3. Amounts and composition of manure

Table 4 presents the manure characteristics. The differences between manure from the two experimental pens were statistically not significant for all parameters. The amount of supplied straw and the collected manure per sow were 0.9 and 2.8 kg/d, respectively. The manures contained 11.0 g N and 1.9 g NH_4^+-N per kg of manure.

Table 4 - Manure characteristics as influenced by floor type -partly bedded floor (PBF) or fully bedded floor (FBF)- in gestating sows (least-square means)

Manure characteristics	Floor type		SEM	Significance
	PBF (n=6)	FBF (n=6)		
Supplied straw (kg/d.sow)	0.90	0.90	0.10	NS
Collected manure (kg/d.sow)	2.97	2.62	0.29	NS
Manure composition				
Dry matter (%)	32.8	31.8	1.6	NS
Organic matter (%)	27.9	26.7	1.3	NS
pH	8.61	8.56	0.13	NS
C/N	13.6	14.5	1.1	NS
Total nitrogen (g N/kg manure)	11.5	10.5	0.7	NS
Ammonium nitrogen (g NH_4^+-N/kg manure)	2.10	1.71	0.48	NS

n: Numbre of samples; SEM: Standard error of the means; F: Floor type; B: Batch;
Significance: NS: P>0.05

3.4. Gas emissions

Table 5 presents the overall means of gas emissions and Figure 2 shows the evolution of the gas emissions from the beginning to the end of the experiment. Breeding sows on partly bedded floor rather than on fully bedded floor did not change NH_3-emissions ($P > 0.05$), increased CH_4-emissions by 29% ($P < 0.001$), direct CO_2-emissions by 8% ($P < 0.01$) and H_2O-emissions by 17% ($P < 0.001$) and, decreased N_2O-emissions by 49% ($P < 0.001$) and CO_{2eq}-emissions by 41% ($P < 0.001$).

While in PBF room, NH_3-emissions increased between the two first weeks of measurements and remained stable around 9.5 g/d per sow thereafter, the emissions in FBF room were similar during the two first weeks and decreased during the third week to reach 5.88 g NH_3/d per sow. In PBF room, N_2O-emissions increased continually throughout the three periods of measurements from 1.34 to 5.14 g/d per sow, while in FBF room, N_2O-emissions greatly increased between each week of measurements (7-

and 1.5-fold, respectively) to reach 10.3 g/d per sow during the third week. For both treatments, CH_4- and CO_2-emissions remained quite stable during the first two weeks of measurements and increased during the third week. Evolution of H_2O-emissions showed no particular trends throughout the experiment.

3.5. Nitrogen balance

Feed and straw provided 91% and 9% of N-inputs, respectively (Table 6). Regarding N-balance, there was no significant difference between treatments for N-retention, N-manure, NH_3-N and N_2O-N with on average 12.7, 30.6, 6.6 and 3.0 g N/d.sow, respectively. Unaccounted-N amounted to about 13.8% of output. Part of this can be considered as unmeasured dinitrogen (N_2) emissions or nitric oxide (NO). The homogenisation and the sampling of the manures can also constitute a source of error. The discrepancy between N-inputs and N-outputs can also be attributed to the measurement schedule: NH_3 and N_2O were measured during targeted periods (3 periods of 6 days per batch) while data for N-feed, N-straw and N-manure were representative of the entire housing period.

Table 5 - Gas emissions (/day.sow) as influenced the floor type -partly bedded floor (PBF) or fully bedded floor (FBF)- in gestating sows (least-square means)

Gas emissions	Floor type		SEM	Significance			
	PBF	FBF		F	W	F x W	B
NH_3 (g)	8.36	7.45	0.30	NS	NS	***	NS
N_2O (g)	3.14	6.12	0.19	***	***	***	**
CH_4 (g)	12.76	9.90	0.27	***	***	**	**
CO_2eq (kg)	1.24	2.10	0.06	***	***	***	**
CO_2 (kg)	3.12	2.90	0.04	**	***	NS	***
H_2O (kg)	4.70	4.03	0.09	***	**	NS	***

SEM: Standard error of the means; F: Floor type; W: Week of measurement; B: Batch; Significance: NS: $P>0.05$; **: $P<0.01$; ***: $P<0.001$

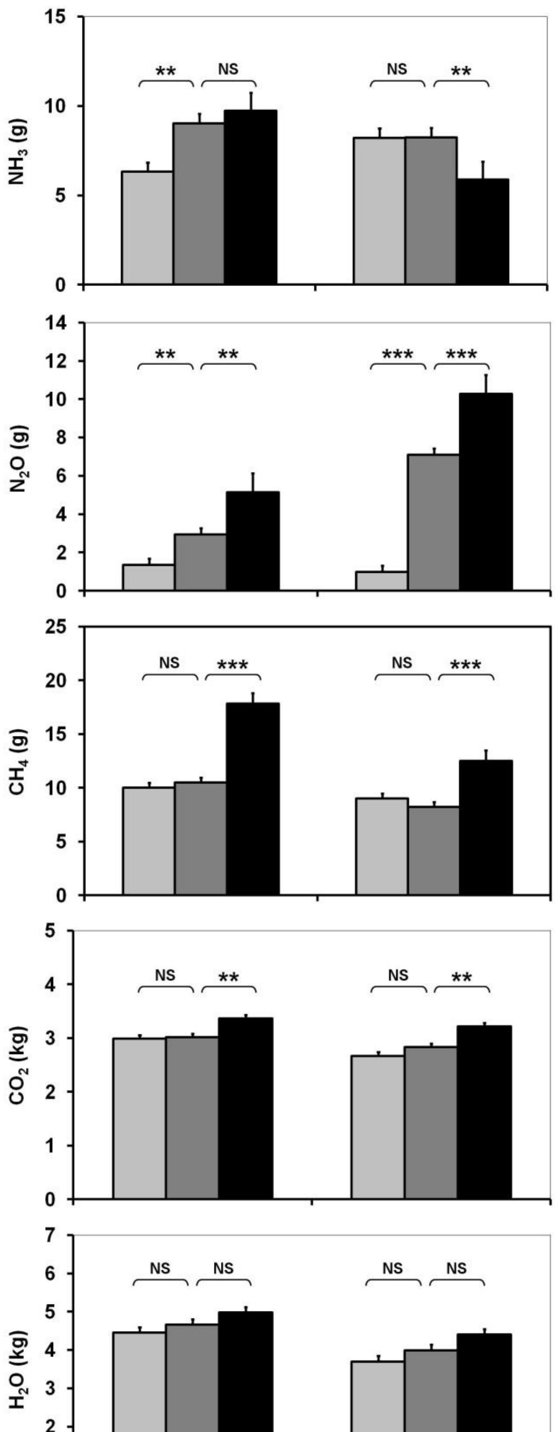

Figure 2 - Gas emissions per day and per sow (least-square means ± standard error) as influenced by floor type (partly bedded floor, PBF, or fully bedded floor, FBF) in gestating sows according to week of measurement (light grey, dark grey and black bars for weeks 2, 5 and 8 respectively; Significance between week of measurement: NS: *P*>0.05; *: *P*<0.05; **: *P*<0.01; ***: *P*<0.001)

Table 6 - Nitrogen balance (g N/d.sow) as influenced by floor type -partly bedded floor (PBF) or fully bedded floor (FBF)- in gestating sows (least-square means)

Nitrogen balance	Floor type		SEM	Significance
	PBF (n=3)	FBF (n=3)		
N-inputs				
N-straw	5.6 (9%)	5.6 (9%)	0.6	NS
N-feed	55.5 (91%)	55.5 (91%)	1.4	NS
N-outputs				
N-retention (estimated)	13.4 (22%)	11.9 (20%)	1.2	NS
N-manure	33.7 (55%)	27.4 (45%)	2.7	NS
NH_3-N	6.9 (12%)	6.2 (10%)	0.4	NS
N_2O-N	2.0 (3%)	3.9 (6%)	0.7	NS
Unaccounted-N	5.0 (8%)	11.7 (19%)	2.0	NS

n: Numbre of experimental units; SEM: Standard error of the means; F: Floor type; B: Batch

3.6. Behavioural observations

In the PBF pen, outside of feeding periods (23 hours per day), all the sows staid together on litter during 40% of the time, what means that the feeding stalls were totally unoccupied during about 555 min per day (figure 3). On average, the feeding stalls were occupied by 1 sow during 493 min per day, by 2 sows during 225 min per day, by 3 sows during 83 min per day and by 4 sows during 32 min per day. During the selected days of recording, there were never 5 sows simultaneously in the feeding stalls.

Outside the feeding periods, the occupation rate of the feeding stalls was on average 19.1%. During the postprandial time, the sows were mainly in the feeding stalls during the 3 hours after the feeding or the 3 hours before the next feeding (figure 4).

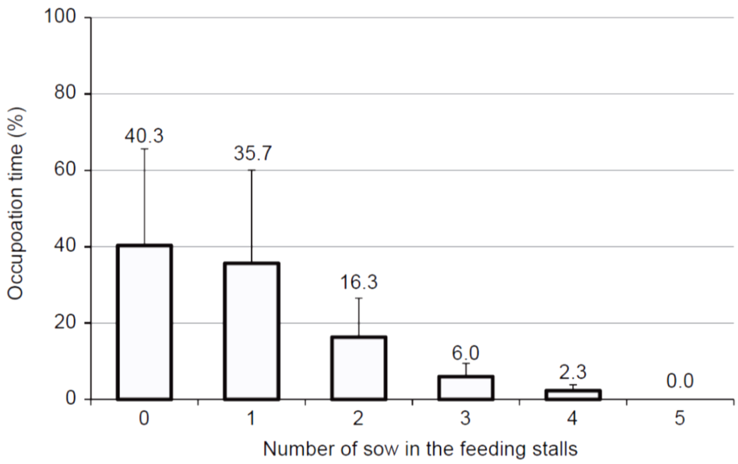

Figure 3 - Occupation time of the feeding stalls by gestating sows outside feeding times (data collected from video recordings, mean ± standard deviation between the 3 batches; 8 days of measurements per batch)

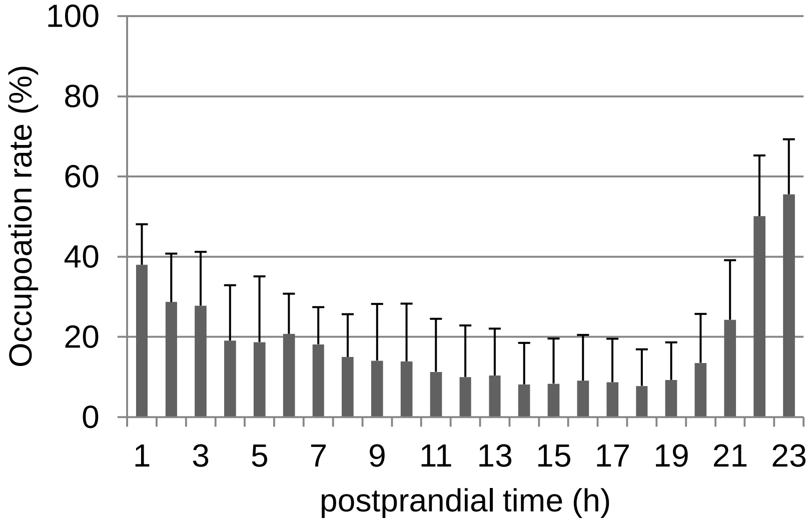

Figure 4 - Occupation rate of the feeding stalls by gestating sows according to postprandial time (data collected from video recording, for each hour, mean ± standard deviation between the 3 batches; 8 days of measurements per batch)

4. Discussion

Ammonia emissions observed in this experiment (7.9 g/d per sow) met the lowest values presented in the literature ranging from 6 to 30 g/d per sow for group-housed sows kept on litter (Groot Koerkamp *et al.*, 1998; Misselbrook *et al.*, 2000; Dore *et al.*, 2004; Philippe *et al.*, 2009). The most important factor influencing the NH_3 emission level from deep litter is the type of bedding material. Usually, litters are made of straw or sawdust, but wood shaving or peat can also be used (Jeppsson, 1998; Robin *et al.*, 1999; Nicks *et al.*, 2004). Several studies showed that NH_3 emissions from sawdust-based deep litter are lower than from straw-based deep litter (Nicks *et al.*, 2003 and 2004; Cabaraux *et al.*, 2009). Jeppsson (1998) demonstrated that bedding materials with low pH, high C/N ratio and easy degradable carbohydrates as an energy source for N immobilization are effective to reduce emissions. Moreover, the physical structure as well as density and moisture content of the litter influence emissions thanks to the effect on gas diffusion, protection from air turbulence and capacity to absorb NH_3 (Dewes, 1996). Other important factors impacting NH_3 emissions are the amount of litter used (with lower emissions when the amount is higher (Gilhespy *et al.*; 2009)), and the size of the emitting area (with lower emissions when the surface is reduced (Philippe *et al.*, 2010)). When bedded areas are combined with concrete floor and/or slatted floor, emissions are depending on the localisation of urine deposition. Emissions increase with a higher frequency of urine deposition on the concrete floor (Groenestein *et al.*, 2007). Indeed, the urease activity on a concrete floor is rapid and important with the volatilization peak occurring 2 to 3 hours after application of urine samples (Elzing and Monteny, 1997; Braam and Swierstra, 1999; Groenestein *et al.*, 2007).

In this experiment, no significant difference was observed between the 2 deep-litter systems. The greater amount of urine and faeces on the concrete floor of the feeding stalls in the PBF room, due to the permanent access of the sows to these stalls in that room, could have compensated for the greater emitting surface of the litter in the FBF room and thus, could explain the results.

Methane emissions observed in this experiment were significantly higher with the 1.8 m^2 litter area compared with the 3 m^2 area (12.8 *vs.* 9.9 g/d per sow). In literature, large variations were observed between authors with values ranging from 5 to 60 g/d per sow (Groot Koerkamp and Uenk, 1997; Godbout *et al.*, 2003; Dong *et al.*, 2007, Philippe *et al.*; 2010). In pig building the two main sources of CH_4 emissions are the animal digestive tract and the manure. The enteric production of CH_4 (g/d) is a function of fibre intakes and can be calculated with the following equation:

[5] $CH_4 = 7.05\ NSP + 3.05$

with NSP, the amount of ingested non starch polysaccharides (kg/d) (Philippe *et al.*, 2008). The CH_4-production from the digestive tract can be estimated at about 8.1 g/d per sow for the two treatments because feed intakes were similar. The CH_4-emissions from the bedding fermentation could be thus estimated at 4.7 *vs.* 1.8 g/d per sow from PBF and FBF rooms respectively. As the amount of provided straw was similar in the two treatments, the higher CH_4-emission reported from the PBF room could be related to greater compaction of the litter due to the higher animal density and thus by the presence of more anaerobic conditions in the litter resulting in an increase of fermentations. Same results were observed by Philippe *et al.* (2010) with higher CH_4-emissions from a deep litter with 2.5 m^2 per sow compared with a 3.0 m^2 deep litter per sow (15.2 *vs.* 10.2 g/d per sow).

A great aeration of the FBF litter could explain the very low emission (1.8 g/d per sow) reported from the litter fermentation. The importance of the waste aeration on CH_4-emissions can also be illustrated by straw/sawdust litter comparison and slurry/litter comparison. Studies about the impact of the type of litter on emission showed lower

CH_4-emissions with sawdust- rather than straw- deep litter (Nicks et al., 2003 and 2004; Cabaraux et al., 2009). Difference in porosity and aeration of the bedding material may explain these results. Slurry/litter comparisons showed that the anaerobic nature of the slurry favour CH_4-production compared to the litter (IPCC, 2006; Philippe et al., 2011). Data of this experiment did not take into account emissions during manure handling and storage. So the emission levels are much lower than data reported by IPCC (2006) with a CH_4-emissions factor of 7 kg/year per head (19 g/d) for breeding swine, when solid based systems are used for the majority of the manure.

Nitrous oxide is produced during nitrification/denitrification processes that normally convert NH_3 into N_2, a non-polluting gas. N_2O is mainly synthesized during denitrification, in the presence of oxygen and/or in case of low availability of degradable carbohydrates (Poth and Focht, 1985). N_2O can also be synthesized during nitrification where there is a lack of oxygen and/or a nitrite accumulation (Groenestein and Van Faassen, 1996; Degre *et al.*, 2001). Thus N_2O-synthesis needs close combination of aerobic and anaerobic areas, heterogeneous conditions met within the litter (Veeken *et al.*, 2002). These particular conditions explain greater N_2O-emissions usually observed with bedded systems in comparison with slurry systems where the environment is largely anaerobic with for example: 0.54 vs. 1.11 g N_2O/d per fattening pig (Philippe *et al.*, 2007a) and 0.47 vs. 2.27 g N_2O/d per gestating sow (Philippe et al., 2011). Relative to straw litter, N_2O emissions are larger with sawdust litter (Nicks *et al.*, 2003 and 2004; Cabaraux *et al.*, 2009). The higher biodegradability of sawdust is suggested to explain these findings (Veeken *et al.*, 2001). For sows kept on litter, Gac *et al.* (2007) reported N_2O-emissions at about 9 g/d per sow. In the current trial, emissions at 3 and 6 g N_2O/d per sow were observed from PBF and FBF rooms, respectively. Thus, the higher animal density in the PBF bedded-area is related to lower N_2O emissions, which is in opposition with findings of Robin *et al.* (2004) and Philippe *et al.* (2010). This discrepancy illustrates the low predictability of level of N_2O emissions from litter that greatly depends of particular conditions interacting inside the manure. More favourable conditions in the FBF litter where close combination of aerobic and anaerobic areas were plausibly more present probably explained the greater N_2O-emissions.
Moreover, the increasing CH_4- and N_2O-emissions with the course of time can be explained by the evolution of the environment inside the bedded-area with dejections accumulation and compaction of the litter throughout the time.

The emissions of CO_2eq calculated in this trial were 69% greater with the FBF despite lower CH_4-emissions from this room. This was due to the elevated direct N_2O-emission and its high GWP. Indeed, in PBF room, about 1.24 kg CO_2eq/d were emitted per sow, 24% coming from CH_4-emissions, 73 % from direct N_2O-emissions and 3% from indirect N_2O-emissions. The corresponding values from the FBF room were 11%, 87% and 2%, respectively, with total CO_2eq-emissions of 2.10 kg/d per sow.

In spite of the low predictability of N_2O emissions from litters, it appears that CO_2eq-emissions from litter systems are higher than from slurry systems. This disadvantage for the litter system could however be compensated within the framework of a global comparison by other advantages in relation, for example, with lower NH_3-emissions (Philippe et al., 2011), some animal welfare improvements, an odour nuisance reduction, a better brand image, the availability or not of litter... This comparison is however not in touch with the objective of this study and a literature review remains to do.

The CO_2 production from piggeries originates mainly from animal respiration but also from manure releases. CO_2-exhalation by pigs is function of energy metabolism (CIGR, 2002; Pedersen *et al.*, 2008). CIGR (2002) proposed an estimation of CO_2-exhalation based on animal body weight and feed intake. In the present trial, these parameters are similar for the two housing conditions. Therefore, the respiratory CO_2-production is estimated at about 2.8 kg/d per sow for both treatments. By deduction, CO_2-emissions from manure can be evaluated at about 0.10 and 0.32 kg/d per sow from FBF and PBF rooms, respectively, representing 3 and 10% of total emissions, respectively. With fattening pigs on litter, Philippe *et al.* (2012) estimated releases from manure at 0.15-0.35 kg/d, i.e. 10-20% of total production. Jeppsson (2000 and 2002) showed that production from bedding can be of the same size as from animal respiration. In manure, the formation of CO_2 comes from (1) the rapid hydrolysis of urea into NH_3 and CO_2, (2) the anaerobic fermentation of manure, and (3) the aerobic degradation of organic material (Jeppsson, 2000). This latter process, called composting, is the principal origin of CO_2 from manure (Møller et al., 2004; Wolter et al., 2004). It is influenced by numerous factors like temperature, moisture content, C/N ratio, pH level, oxygen level and the physical structure of the organic material (Jeppsson, 2000). Cabaraux et al. (2009) measured CO_2 emissions of 334 and 427 g/d for weaned piglets kept on sawdust and straw deep litter, respectively. Nicks et al. (2003 and 2004) reported quite similar emission factor for both litter type as well with weaned piglets as fattening pigs. Assuming similar respiratory production for the two treatments, the significant greater CO_2-emissions observed from the PBF room could be explained by the difference of physico-chemical conditions inside the litter. The greater CO_2-emissions observed at the end of the experiment could be explained by the greater metabolism of the sows at the end of the gestation (Van Milgen et al., 2000) and the accumulation of manure over the course of time.

Like CH_4 and CO_2, H_2O-emissions have two origins: animals and manure. Evaporation by animals is function of body weight, heat production and ambient temperature and can be estimated at 3.3 kg/d per sow for both treatments (CIGR, 2002). By difference, evaporation from manure can be estimated at 1.4 and 0.7 kg/d per sow for PBF and FBF rooms, respectively, representing 30 and 17% of total emissions, respectively. Evaporation from manure is influenced by litter characteristics, like aeration, dry matter content and C/N ratio that modulate microbial activity inside the litter. High microbial activity is related to high litter temperature and high water vapour emissions as consequence. Usually, reported litter temperature are around 30-40°C (Nicks, 2004). Comparisons between straw and sawdust litters showed larger emissions from the latter (Nicks et al., 2003 and 2004; Cabaraux et al., 2009) probably because of the higher water content of the sawdust and its higher biodegradability (Veeken et al., 2001). Metabolic water formation inside the litter also influences the level of evaporation from manure (Rigolot et al., 2010). In addition to conditions inside the litter, animal behaviours like resting, rooting, drinking and excreting activity may influence H_2O-evaporation from manure. All these phenomena interacted and contributed to greater H_2O-evaporation from the PBF room.

5. Conclusion

It can be concluded that keeping group-housed gestating sows on partly straw bedded floor with permanent access to the concrete feeding stalls compared to fully straw bedded floor did not significantly influence animal performance and NH_3-emissions, and decreased CO_2eq-emissions (-40%). This decrease was observed despite an increase of CH_4-emissions and owing to an important decrease of N_2O-emissions (-49%) that has a high global warming potential.

However, these conclusions have to take into account the scale of the experimental rooms, with only 5 sows per group. Indeed, increasing the size of the group probably would decrease the proportion of the area fouled with manure because of typical excreting behaviour of sows. This could thus influence the levels of gaseous emissions but probably not the results of the comparison of the two housing conditions which is one criterion among others, such as building and bedding costs, animal behaviour, farmer habits and customs, animal welfare… contributing to the choice for the sow housing.

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Discussion générale

Le tableau 1 reprend l'ensemble des résultats d'émissions gazeuses obtenus lors des expérimentations intégrées à cette étude.

Tableau 1 – Récapitulatif des résultats d'émissions gazeuses obtenus lors des expériences successives

	Emissions gazeuses (animal^{-1} jour^{-1})			
	NH_3 (g)	**N_2O (g)**	**CH_4 (g)**	**CO_2 (kg)**
Etude 1 – Porcs charcutiers				
Caillebotis total	6.22^a	0.54^a	16.32	1.74^a
Paille accumulée	13.10^b	1.11^b	16.03	1.97^b
Etude 2 – Truies gestantes				
Caillebotis total	12.77^a	0.47^a	10.12^a	2.41^a
Paille accumulée	9.05^b	2.27^b	9.20^b	2.83^b
Etude 3 – Truies gestantes				
Paille accumulée – 2,5 m^2 truie^{-1}	6.52^a	3.90^a	15.21^a	2.41^a
Paille accumulée – 3,0 m^2 truie^{-1}	7.64^b	2.80^b	10.15^b	2.12^b
Etude 4 – Porcs charcutiers				
Paille accumulée – 50 kg paille	19.04^a	1.11^a	4.83^a	2.40
Paille accumulée – 75 kg paille	18.24^a	0.87^b	7.33^b	2.50
Paille accumulée – 100 kg paille	16.04^b	0.74^c	9.09^c	2.46
Etude 5 – Porcs charcutiers				
Paille accumulée	12.1^a	1.50^a	16.50^a	1.97^a
Litière glissante	13.3^b	0.68^b	8.90^b	1.77^b
Etude 6 – Truies gestantes				
Sol totalement paillé	7.45	6.12^a	9.90^a	2.90^a
Sol partiellement paillé	8.36	3.14^a	12.76^b	3.12^b

^{a,b,c} : Au sein d'une même étude, pour un même gaz, les valeurs agrémentées de lettres différentes sont significativement différentes entre elles ($P<0,05$)

1. LES EMISSIONS D'AMMONIAC

Les émissions de NH_3 mesurées lors des présentes études portant sur les porcs charcutiers ont été en moyenne de 6,2 g NH_3 porc^{-1} jour^{-1} avec le système à caillebotis et ont variés de 12,1 à 19,0 g NH_3 porc^{-1} jour^{-1} avec les systèmes paillés. Pour les truies gestantes, les émissions ont été de 12,8 g NH_3 truie^{-1} jour^{-1} avec le système à caillebotis contre 6,5 à 9,1 g NH_3 truie^{-1} jour^{-1} avec les systèmes paillés. De nombreux facteurs d'émissions sont rapportés dans la littérature concernant l'hébergement sur caillebotis avec des valeurs allant de 4 à 14 g NH_3 jour^{-1} pour des porcs charcutiers (Aarnink et al., 1995 ; Groot Koerkamp et al., 1998 ; Robin et al., 1999; Fernandez et al., 1999; Nicholson et al., 2000; Balsdon et al., 2000; Guingand et Granier, 2001; Kermarrec et Robin, 2002; Guingand, 2003 ; Sun et al., 2008 ; Guingand et al., 2010) et de 8 à 16 g NH_3 jour^{-1} pour des truies gestantes (Groot Koerkamp et al., 1998 ; Dourmad et al., 1999 ; van der Peet-Schwering et al., 1999 ; Misselbrook et al., 2000 ; Groenstien et al., 2003 ; Hyde et al., 2003 ; Dore et al., 2004 ; Hayes et al., 2006). Les études relatives au logement sur litière sont plus rares, avec des émissions allant de 3 à 22 g NH_3 jour^{-1} pour des porcs charcutiers, (Groot Koerkamp et al., 1998 ; Nicholson et al., 2000; Balsdon et al., 2000 ; Nicks et al., 2004 ; Guingand et Rugani, 2013) et de 6 à 31 g NH_3 jour^{-1} pour des truies gestantes (Groot Koerkamp et al., 1998 ; Misselbrook et al., 2000 ; Dore et al., 2004). Les émissions obtenues durant les expérimentations de la présente étude rejoignent donc les valeurs citées dans la littérature. La variabilité des facteurs d'émission présentés, quel que soit le type de sol, peut provenir des conditions expérimentales différentes entre les études (par exemple : poids corporel, densité animale, stratégie alimentaire, gestion des effluents, système d'évacuation et de nettoyage, conditions d'ambiance, saison et méthode de mesure). A l'inverse, les conditions expérimentales de la présente étude étaient totalemet standardisées et contrôlées, ce qui a permis des comparaisons rigoureuses entre différents systèmes de logement.

Les études comparées d'émissions de NH_3 entre les systèmes sur caillebotis et paille accumulée ont montré des émissions tantôt plus élevées à partir des litières (porcs charcutiers) tantôt à partir des lisiers (truies gestantes). Des résultats contradictoires sont également présentés dans la littérature avec des émissions favorisées dans l'un ou l'autre système (Robin et al., 1999 ; Balsdon et al., 2000 ; Nicholson et al., 2000 ;

Kermarrec et al., 2002, Kavolelis, 2006 ; Kim et al., 2008 ; Cabaraux et al., 2009). On peut expliquer ces résultats par la diversité de systèmes au sein des logements sur litière qui regroupent un grand nombre de modalités différentes qui peuvent différer par le type de substrat (paille, sciure, copeaux de bois,…), l'importance et la fréquence des apports, l'espace disponible et le mode d'évacuation des fumiers (Ramonet et Dappelo, 2003). Ces paramètres modifient les propriétés physiques et chimiques des litières, avec des répercussions sur les émissions de NH_3 (Dewes, 1996 ; Jeppsson, 1998). Les hypothèses avancées pour expliquer les résultats opposés des deux premières études se basaient sur les effets de la surface disponible et de la quantité de paille apportée.

Les porcs charcutiers élevés sur paille disposaient d'une surface plus grande que ceux logés sur caillebotis (1,20 *versus* 0,76 m^2 par porc) alors que la surface disponible était identique pour les deux types de sol avec les truies gestantes (2,5 m^2 par truie). En augmentant l'espace disponible, l'interface entre la litière et l'air est plus grande, ce qui augmente la surface d'émissions du NH_3. Cela a pu être confirmé dans l'étude 3 menée avec des truies gestantes élevées sur paille accumulée et disposant de 2,5 ou 3,0 m^2. En accroissant la surface disponible de 20%, la production de NH_3 a été augmentée de 17%. Avec des porcs à l'engrais élevé sur caillebotis, Guingand (2007) avait observé des émissions augmentées de 35% avec une surface disponible augmentées de 43%. A l'inverse, Basset-Mens et al. (2007) et Rigolot et al. (2010) associent des émissions plus élevées à une surface paillée réduite. Ils justifient cela par des températures ambiantes et des ventilations plus élevées dues à la plus grande densité animale, et des conditions favorables aux réactions de nitrification/dénitrification dans les litières aboutissant à la synthèse de N_2 au détriment du NH_3.

Outre la surface disponible, les apports de paille différaient également entre porcs charcutiers et truies gestantes (respectivement 390 et 920 g $jour^{-1}$ $animal^{-1}$), alors que les rejets d'azote étaient proches pour les deux catégories d'animaux, évalués à environ 40 g N $jour^{-1}$ $animal^{-1}$. Un rapport C/N du fumier qui serait augmenté par l'apport supplémentaire de paille est supposé réduire les émissions de NH_3 car le carbone peut servir de source d'énergie aux bactéries qui assimilent l'azote disponible en protéines microbiennes plus stables (Jeppson, 1998). C'est ce qui a été vérifié dans l'étude 4 menée avec des porcs charcutiers où l'augmentation de la quantité de paille de 50 à 100 kg par porc (550 à 1100 g $jour^{-1}$ $animal^{-1}$) s'est traduite par une réduction des émissions de NH_3 de 16% (19 *versus* 16 g NH_3 $porc^{-1}$ $jour^{-1}$). Ce résultat est très proche de celui de Gilhepsy et al. (2009) qui avaient mesuré des émissions réduites de 18% en augmentant le taux de paillage de 4 à 8 kg $porc^{-1}$ $semaine^{-1}$. De même, Guingand et Rugani (2013) ont observé une réduction de la production de NH_3 de près de 25% en passant de 60 à 90 kg de paille par porc. Tous ces résultats remettent en question la position de Rigolot et al. (2010) qui soutenaient que les émissions de NH_3 n'étaient pas influencées par le paillage pour des quantités comprises entre 30 et 100 kg de paille par animal.

Le mode d'hébergement sur litière glissante a été associé à des émissions plus élevées que le système avec paille accumulée (étude 5), malgré la surface disponible réduite et l'évacuation fréquente des effluents associée à la séparation des phases solides et liquides. Plusieurs études ont pourtant montré que ces deux techniques étaient efficaces pour réduire significativement les émissions de NH_3, aussi bien dans des systèmes lattés que paillés (Godbout et al., 2006; Kavolelis, 2006 ; Landrain et al., 2009 ; Lagadec et al., 2012). L'utilisation de quantités moindres de paille, la manipulation des fumiers lors des activités de raclage et le stockage, même temporaire, du fumier dans le local contribuent à expliquer les émissions plus élevées observées. De plus, la synthèse rapide de NH_3 lorsque l'urine est en contact avec un sol bétonné peut justifier ce résultat. Des travaux ont effectivement montré des pics d'émission importants 2-3 heures après l'application d'échantillons d'urine sur des surfaces bétonnées (Elzing et Monteny, 1997; Braam et Swierstra, 1999; Groenestein et al., 2007). Ce phénomène explique également l'absence de différence significative entre les loges totalement paillées et partiellement paillées dans l'expérience avec des truies gestantes ayant accès ou non à la zone d'alimentation bétonnée mais disposant de la même surface totale (étude 6). La réduction de la surface d'émission de la zone paillée a été compensée par la présence de déjections sur l'aire bétonnée. En effet, la localisation des endroits de dépôt des déjections peut avoir un impact important sur les niveaux d'émission. Dans une loge pour truies gestantes combinant zones paillées, bétonnées et lattées, Groenstein et al. (2007) ont observé une diminution des émissions de NH_3 quand la fréquence de miction était augmentée en zone paillée. La conception même des locaux doit donc favoriser la tendance naturelle des porcs à séparer spacialement leur comportements d'alimentation, d'excrétion et de repos afin de préserver la propreté globale des loges (Aarnink et al., 1996).

2. LES EMISSIONS DE PROTOXYDE D'AZOTE

Le N_2O est essentiellement produit durant les réactions de nitrification/dénitrification effectuées par des bactéries qui convertissent l'ammonium (NH_4^+) en diazote (N_2), gaz non-polluant. En tant que sous-produit de ces réactions, sa synthèse est favorisée lorsque les conditions ne sont pas réunies pour permettre un accomplissement complet du processus. Durant la nitrification, il est produit en cas de manque d'oxygène et/ou d'accumulation de nitrites. Durant la dénitrification, il est produit en présence d'oxygène et/ou en cas de manque en hydrates de carbone dégradables (Poth et Focht, 1985; Driemer et Van den Weghe, 1997). La formation du N_2O nécessite donc la combinaison de zones aérobies étroitement liées à des zones anaérobies. La plupart des bactéries nitrifiantes et dénitrifiantes étant mésophiles, sa synthèse est généralement inhibée à des températures supérieures à 40-50°C (Hellmann et al., 1997; Kebreab et al., 2006).

Les lisiers, par le caractère anaérobie, sont peu producteurs de N_2O. La formation d'une croûte à leur surface peut cependant fournir des conditions favorables à sa synthèse. Dans nos études, les émissions associées aux systèmes à caillebotis pour porcs charcutiers et pour truies gestantes ont été proches de 0,5 g N_2O animal^{-1} jour^{-1}. L'environnement hétérogène rencontré au sein des litières a favorisé la formation de N_2O avec des émissions allant de 0,7 à plus de 6 g N_2O animal^{-1} jour^{-1}. Ces valeurs rejoignent celles de la littérature avec des émissions allant de 0,3 à 1,2 g N_2O animal^{-1} jour^{-1} pour des sols à caillebotis et de 1 à 10 g N_2O animal^{-1} jour^{-1} pour des sols avec litière (Sneath et al., 1997 ; Fitament et al., 1999 ; Robin et al., 1999 ; Lägue et al., 2004 ; Nicks et al., 2004 ; Kermarrec et al., 2002 ; Hassouna et al., 2005 ; Dong *et al.*, 2007 ; Gac et al., 2007 ; Costa et Guarino, 2009 ; Guingand et al., 2010 ; Guingand et al., 2013 ; Vandré et al., 2013).

Tous les paramètres qui modifient les propriétés physico-chimiques des fumiers (température, densité, humidité, pH, rapport C/N) ont un impact sur les niveaux de N_2O produit (Dewes, 1996 ; Groenestein et Van Faassen, 1996). Par exemple, le type de substrat influence les émissions, des litières à base de sciure étant davantage émettrices de N_2O que des litières paillées (Groenestein et Van Faassen, 1996; Nicks *et al.*, 2004; Cabaraux *et al.*, 2009). La plus grande biodégradabilité de la sciure (Veeken et al., 2001) et la température moins élevée de la litière liée à sa densité (Jeppsson, 2000) peuvent expliquer ce résultat.

Dans nos expériences, en augmentant l'aération de la litière par l'accroissement de la surface disponible (étude 3) ou l'apport supplémentaire de paille (étude 4), une réduction des émissions a été observée. Des recherches précédentes avaient également abouti aux mêmes constats (Hassouna et al., 2005; Yamulki, 2006 ; Rigolot et al., 2010 ; Guingand et Rugani, 2013). Ainsi, les études d'Hassouna et al. (2005) sur l'effet de la densité animale les conduisent à proposer deux facteurs d'émission pour des porcs charcutiers élevés sur litière : 2-8% ou 4-12% de l'azote excrété pour une surface disponible de plus ou moins 2 m^2 par porc, respectivement. Ces valeurs correspondent à environ 3 et 5 g de N_2O $animal^{-1}$ $jour^{-1}$, respectivement. Les résultats obtenus avec les truies gestantes disposant de 2,5 ou 3,0 m^2 montrent une réduction de 28% avec la plus faible densité animale. En augmentant le taux de paillage de 60 à 90 kg par porc, Guingand et Rugani (2013) diminuent les émissions de N_2O de 57%. Dans notre étude, la production de N_2O est réduite de 33% en passant de 50 à 100 kg par porc.

Avec la litière glissante, on obtient des émissions réduites de moitié en comparaison à la paille accumulée, alors que la quantité de paille et la surface disponible étaient plus faibles (étude 5). Néanmoins, l'aspect de cette litière était plus aéré aussi bien au niveau de la loge que du tas de fumier, en raison des manipulations journalières de raclage et de l'absence de tassement par les animaux. Le résultat obtenu avec les truies ayant un accès permanent à la zone d'alimentation bétonnée paraît plus difficile à expliquer, avec des émissions plus faibles associées à la plus petite zone paillée (étude 6). L'occupation préférentielle des truies pour la surface paillée y conduit à un plus grand tassement de la litière, ce qui est supposé augmenter les émissions (Veeken et al., 2002). Des conditions particulières au sein des fumiers pourraient justifier ce résultat opposé. Le niveau d'émission reste tout de même plus élevé que ceux rencontrés avec les lisiers. Ce résultat discordant illustre la grande variabilité des émissions de N_2O à partir des litières dont la production est rendue peu prévisible compte tenu de la complexité des ses voies de synthèse.

3. LES EMISSIONS DE METHANE

Les émissions de CH_4 mesurées dans ces études ont varié de 5 à 16 g CH_4 porc^{-1} jour^{-1} en présence de porcs charcutiers et de 10 à 15 g CH_4 truie^{-1}jour^{-1} en présence de truies gestantes, quel que soit le mode d'hébergement. La littérature montre une grande variabilité des niveaux d'émission d'une étude à l'autre mais également au sein d'une même étude. Par exemple, Costa et Guarino (2009) présentent des émissions allant de 15,0 à 161,1 g CH_4 truie^{-1} jour^{-1} pour des lots successifs de truies logées dans la même porcherie. La bibliographie relatant les émissions associées à l'élevage de porcs charcutiers rapporte des valeurs allant de 2,0 à 43,0 g CH_4 porc^{-1} jour^{-1} (Groot Koerkam et Uenk, 1997 ; Osada et al., 1998 ; Ball et al., 2003 ; Guarino et al., 2003 ; Lägue et al., 2004 ; Haessermann et al., 2006 ; Guarino et al., 2008 ; Costa et Guarino, 2009 ; Palkovicova et al., 2009 ; Ngwabie et al., 2011). Parmi les paramètres explicatifs de cette variabilité, le temps de séjour des effluents à l'intérieur des bâtiments joue un rôle déterminant, réduire la fréquence d'évacuation des effluents augmentant fortement la production de CH_4 (Moller et al., 2004 ; IPCC, 2006).

La formation de CH_4 provient de la dégradation strictement anaérobie de la matière organique (Hellmann et al., 1997). En porcherie, les deux sources principales sont le tube digestif des animaux et les fermentations de l'effluent.

La production entérique dépend de la teneur en fibres de la ration et de la capacité fermentaire des animaux. En incorporant 30% de pulpes de betteraves comme source de fibres dans un aliment pour porcs charcutiers, Rijnen et al. (2001) ont constaté une augmentation des émissions entériques de 3.7 à 8.0 g CH_4 porc^{-1} jour^{-1}. L'origine botanique, la solubilité et la fermentescibilité des fibres influencent le niveau de production (Philippe et al., 2008). La capacité fermentaire des animaux dépend du poids corporel et du stade physiologique (Le Goff et al., 2002c ; Galassi et al., 2005). Avec des apports en fibres identiques, la production de CH_4 est plus élevée chez des truies adultes que chez des porcs en croissance (Le Goff et al., 2002c). En compilant différentes données de la littérature, les relations suivantes ont pu être établies afin de calculer la production de CH_4 par les porcs charcutiers et les truies gestantes (respectivement E-$CH_{4,porc}$ et E-$CH_{4,truie}$, en g CH_4 jour^{-1}) à partir des consommations alimentaires de résidus digestibles (dRes, en g $jour^{-1}$, définis par l'INRA-AFZ (2004) comme la différence entre la matière organique digestible et les protéines, graisses, amidon et sucres digestible) :

$$E - CH_{4,porc} = 0.012 \times dRes \; (R^2 = 0.77),$$

$$E - CH_{4,truie} = 0.021 \times dRes \; (R^2 = 0.90).$$

Ces équations permettent d'évaluer la production digestive des animaux utilisés dans nos études, à savoir environ 3 g CH_4 $jour^{-1}$ pour les porcs charcutiers et 8 g CH_4 $jour^{-1}$ pour les truies gestantes. Cette estimation ne tient pas compte des ingestions éventuelles de paille par les animaux logés sur litière. Pour des porcs charcutiers, Staals et al. (2007) évaluent ces consommations entre 96 et 234 g MS $jour^{-1}$, ce qui correspondrait à environ 1 g CH_4 produit lors des fermentations entériques. On s'attend à des valeurs plus élevées pour des truies gestantes, sans pour autant pouvoir fournir une estimation précise. Les différences observées entre les modes de logement testés dans cette étude proviendraient essentiellement des caractéristiques propres aux effluents.

Dans les effluents, la méthanogenèse par les bactéries est favorisée par une température élevée, des conditions anaérobies, des teneurs importantes en matière organique dégradable, une teneur élevée en eau, un pH neutre, un rapport C/N compris entre 15 et 30 et un temps de séjour prolongé (Moller et al., 2004; Amon et al., 2006; Kebreab et al., 2006). La production de CH_4 est limitée par un fort taux d'aération et des concentrations élevées en ammonium, acides gras volatils et sulphides qui inhibent la croissance des bactéries méthanogènes (Monteny et al., 2006; Vedrenne et al., 2008; Cerisuelo et al., 2012).

Dans la littérature, on rapporte généralement des émissions plus élevées à partir des lisiers que des fumiers. Ahlgrimm et Bredford (1998) ont mesuré des émissions de 6,16 g CH_4 $porc^{-1}$ $jour^{-1}$ avec un système sur caillebotis contre 2,74 g CH_4 $porc^{-1}$ $jour^{-1}$ avec un système sur litière paillée. Freibauer (2003) évalue la contribution de l'effluent aux émissions totales à partir des bâtiments à 70% avec des lisiers contre 50% avec des litières. Les conditions strictement anaérobies rencontrées au sein des lisiers expliquent ces constats. Néanmoins, la présence d'une croûte à la surface des lisiers peut induire l'oxydation du CH_4 en CO_2 par des bactéries méthanotrophes qui utilisent le CH_4 comme source de carbone en conditions aérobies. De plus, dans les litières, la production de CH_4 peut être favorisée par un rapport C/N et des températures élevés. C'est ce que confirment les résultats de l'étude portant sur l'influence de la quantité de paille sur les émissions (étude 4) où l'augmentation du taux de paillage (+100%) a induit une augmentation de la production de CH_4 (+88%). De même, Guingand et Rugani (2013) ont mesuré des émissions plus élevées (+76%) avec une quantité de paille plus importante (+50%). A l'inverse, d'autres auteurs ont rapporté des émissions réduites avec davantage de paille (Sommer et al., 2000 ; Yamulki, 2006). Dans ce cas, l'hypothèse avancée est qu'un paillage généreux génère une litière fortement aérée, ce qui limite la méthanogenèse. D'ailleurs, dans nos expérimentations, la présence de litières plus aérées, par l'accroissement des surfaces paillées disponibles (études 3 et 6) ou la gestion des fumiers empêchant le tassement par les animaux (étude 5) a permis de réduire la production de CH_4. Compte tenu des différents facteurs d'émissions obtenus dans cette présente étude, il demeure délicat de prendre indubitablement position en faveur de l'un ou l'autre système, la production variant de 5 à 16 g de CH_4 animal^{-1} jour^{-1}, que les animaux soient logés sur caillebotis ou sur litière. Les propriétés spécifiques des effluents modulant le niveau d'émission.

4. Les emissions de dioxyde de carbone

Les émissions de CO_2 mesurées dans ces études ont varié de 1,7 à 2,5 kg CO_2 $porc^{-1}$ $jour^{-1}$ pour les porcs charcutiers et de 2,1 à 3,2 kg CO_2 $porc^{-1}$ $jour^{-1}$ pour les truies gestantes. Ces valeurs rejoignent celles rapportées dans la littérature qui vont de 1,1 à 3,6 kg CO_2 $porc^{-1}$ $jour^{-1}$ pour des porcs charcutiers et de 2,5 à 5,3 kg CO_2 $porc^{-1}$ $jour^{-1}$ pour des truies gestantes (Ball et al., 2003 ; Guarino et al., 2003 ; Gallmann et al., 2003 ; Lägue et al., 2004 ; Nicks et al., 2005 ; Dong et al., 2007 ; Zhang et al., 2007 ; Guarino et al., 2008 ; Costa et Guarino, 2009 ; Palkovicova et al., 2009 ; Guingand et al., 2010 ; Ngwabie et al., 2011 ; Stinn et al., 2011).

Les émissions de CO_2 en porcheries ont pour source principale la respiration des animaux. La production respiratoire dépend du métabolisme des animaux et donc du stade physiologique, du poids corporel, de la température, du taux d'activité, du niveau de production et des ingestions alimentaires (CIGR, 2002 ; Brown-Brandl et al., 2004 ; Pedersen et al., 2008). Différentes méthodes permettent d'estimer le CO_2 exhalé par les porcs charcutiers Pour un poids de 70 kg, on évalue la production respiratoire à environ 1,5 kg CO_2 $porc^{-1}$ $jour^{-1}$ (Ni et al., 1999a ; CIGR, 2002 ; Brown-Brandl et al., 2004 ; Pedersen et al., 2008). Peu de données concernent les truies gestantes. D'après la CIGR (2002), on peut estimer leur production à environ 2,2 kg CO_2 $porc^{-1}$ $jour^{-1}$. Dans les conditions expérimentales de la présente étude, les paramètres qui influencent les émissions respiratoires étaient identiques entre les systèmes étudiés. Les différences observées entre les types de sol sont donc supposées provenir des effluents. En soustrayant la production estimée venant des animaux des émissions totales, on peut évaluer la contribution des lisiers à environ 10% et celle des fumiers à environ 30% en moyenne, alors que les émissions à partir des effluents ont souvent été considérées comme insignifiantes (Anderson et al., 1987; van 't Klooster et Heitlager, 1994). D'autres études récentes concluent également à une production non négligeable à partir des lisiers et fumiers (Ni et al., 1999b ; Jeppsson, 2000 et 2002 ; Pedersen et al., 2008).

Dans l'effluent, trois voies de synthèse ont été identifiées : (1) l'hydrolyse rapide de l'urée en NH_3 et CO_2 ; (2) la fermentation anaérobie de la matière organique avec production d'intermédiaires comme les acides gras volatils, le CH_4 et le CO_2 ; (3) la dégradation aérobie de la matière organique (Jeppsson, 2000; Moller et al., 2004; Wolter et al., 2004). Dans les lisiers, il semblerait que la voie privilégiée soit la dégradation anaérobie (Ni et al., 1999b), alors que dans les fumiers, ce soit la voie aérobie (Hellmann et al., 1997 ; Wolter et al., 2004). Néanmoins, l'importance relative de ces différentes sources d'émission n'est pas toujours aisée à identifier (Moller et al., 2004). Les propriétés physiques et chimiques propres à chaque effluent déterminent la voie de production principale et le niveau d'émission. Parmi les facteurs impliqués, on peut citer la température, le taux d'aération, le rapport C/N, le pH et la teneur en humidité (Andersson, 1996; Jeppsson, 2000; Paillat et al., 2005).

Dans les essais réalisés pour cette étude, les comparaisons entre sols lattés et paillés ont montré des émissions de CO_2 plus élevées d'environ 15% à partir des litières (études 1 et 2), confirmant ainsi des études antérieures (Cabaraux et al., 2009). Le processus de compostage (dégradation aérobie) favorisé au sein des fumiers peut expliquer ce résultat. L'augmentation de la surface paillée a induit une réduction de la production de CO_2 (études 3 et 6). La mise en place d'une litière glissante, combinant évacuation fréquente de l'effluent et séparation de phases, a réduit les émissions de 10% en comparaison à une litière accumulée (étude 5), alors que plusieurs auteurs ont conclu à l'absence d'un effet du mode de gestion de l'effluent sur la production de CO_2 (Osada et al., 1998 ; Guarino et al., 2003 ; Godbout et al., 2006). Enfin, les émissions de CO_2 n'ont pas été impactées significativement par l'augmentation de la quantité de paille de 50 à 100 kg par porc (étude 4). Les conditions particulières rencontrées dans les effluents peuvent contribuer à justifier ces résultats, en favorisant l'une ou l'autre voie de synthèse sans que le mécanisme sous-jacent soit clairement identifié.

La production de CO_2 par les animaux d'élevage et leurs effluents n'est généralement pas prise en compte dans les inventaires d'émissions car on considère qu'elle a été compensée par la photosynthèse des plantes qui constituent l'aliment (Steinfeld et al., 2006 ; IPCC, 2007). Dans nos études, malgré des compositions alimentaires, des ingestions et des performances identiques, des facteurs d'émission différents ont été relevés entre modes de logements. Dès lors, l'éviction du CO_2 des bilans d'émission pourrait être remise en question.

Conclusions et perspectives

La comparaison des émissions de NH_3 entre les systèmes à caillebotis et sur litière de paille accumulée n'a pas permis de conclure avec certitude en faveur de l'un ou l'autre type de sol, chacun d'eux pouvant regrouper des modalités d'hergement différentes qui interfèrent avec les niveaux d'émissions. D'un point de vue environnemental, l'inconvénient principal des systèmes paillés est d'être producteur de plus grandes quantités de N_2O, qui ne sont pas compensées par la réduction des émissions de CH_4 parfois observée. Néanmoins, le niveau de production du N_2O à partir des litières est rendu peu prévisible par son mode de synthèse complexe qui nécessite des conditions particulières au sein des fumiers.

Avec les litières de paille, l'augmentation de la surface disponible par animal a conduit à une élévation des émissions de NH_3. Lorsque le système paillé est associé à un sol en béton, en cas d'accès à une zone d'alimentation bétonnée ou dans le logement sur litière glissante, les émissions de NH_3 sont également augmentées par la présence de déjections sur les parties en sol plein. Par contre, la production de NH_3 est diminuée par un accroissement du taux de paillage. L'apport supplémentaire de paille semble neutre du point de vue des émissions de gaz à effet de serre, la diminution des émissions de N_2O étant compensée par l'augmentation des émissions de CH_4. Les techniques qui empêchent le tassement trop important de la litière (augmentation de l'espace disponible, évacuation rapide des fumiers) réduisent efficacement les émissions de CH_4 mais ont des effets variables sur le N_2O.

Les émissions de CO_2 ont pour source principale la respiration des animaux. La contribution des effluents n'est cependant pas négligeable. Comparé aux lisiers, les litières de paille émettent davantage de CO_2, le processus de compostage y étant favorisé. Des émissions de CO_2 différentes ont été mesurées entre certains modes d'hébergement sur paille sans cause clairement identifiée, les propriétés physico-chimiques des litières interférant entre-elles pour favoriser ou non sa synthèse.

La particularité de cette étude est de comparer plusieurs modes de logement de manière totalement standardisée. Les locaux expérimentaux dans lesquels les différents types de loges ont été aménagés étaient strictement identiques (surface, volume) et les conditions d'ambiance entièrement contrôlées. Cette méthodologie permet de cerner avec précision les paramètres qui font varier les niveaux d'émission toute chose étant égale par ailleurs. De cette manière, des moyens efficaces de réduction peuvent être identifiés. Les facteurs d'émissions issus des expérimentations contribuent également à la constitution de bases de données utiles dans l'élaboration d'inventaires d'émission. *In fine*, les résultats de ces recherches doivent servir aux éleveurs afin de les guider dans leur choix d'un type d'hébergement quant à ses effets sur l'environnement. D'autres éléments devront également être pris en compte comme les effets sur la santé animale, les performances de production, le bien-être animal et bien sûr les répercutions économiques. L'adaptation des techniques en fonction des caractéristiques propres à chaque élevage entraîne une grande diversité dans les systèmes d'hébergement employés, spécialement pour les systèmes avec litière. Idéalement, on devrait pouvoir disposer de facteurs d'émissions spécifiques pour chaque type de logement. Les méthodes actuelles de mesures des gaz sont sophistiquées, coûteuses et difficilement applicables en conditions réelles. La conception d'outils de mesure simples et peu coûteux faciliterait leur utilisation sur le terrain afin de vérifier si les techniques de réduction adoptées sont efficaces et pérennes. Dans un souci de suivi ou de certification, ces outils serviraient d'incitant pour une réduction durable des émissions. La mutualisation des résultats permettrait en outre de déterminer les systèmes les plus performants en fonction de circonstances spécifiques.

Dans le mode hébergement sur litière, des études supplémentaires seraient nécessaires afin d'approfondir les connaissances sur les propriétés physiques, chimiques et biologiques des fumiers et d'en préciser les effets sur les émissions polluantes. Outre la paille ou la sciure, d'autres substrats pourraient être utilisés en fonction de disponibilités particulières (digestat de méthaniseur, paille de miscanthus, paille de chanvre,…). Il serait intéressant de caractériser les émissions relatives à ces litières. Des recherches complémentaires pourraient également concerner les systèmes à caillebotis avec comme objet d'étude le type de matériau employé, la disposition des loges, la conception des fosses et le système d'évacuation du lisier. Des stratégies alimentaires se sont déjà montrées efficaces pour réduire les impacts environnementaux des élevages porcins (réduction du taux de protéines, alimentation multi-phase, acidification des régimes, supplémentation en phytase, …). D'autres techniques alimentaires innovantes pourraient être développées par l'introduction de nouvelles matières premières disponibles (nouveaux co-produits issus de l'industrie agro-alimentaires et des agrocarburants) ou l'utilisation d'additifs aux propriétés particulières. Dans ce cadre, les pré-/pro-biotiques pourraient constituer une piste intéressante. Toute méthode qui améliore la digestibilité des rations, et plus largement qui favorise le potentiel producteur des animaux devrait avoir une influence positive sur les rejets. Ainsi, l'amélioration du statut sanitaire des troupeaux et la sélection génétique peuvent contribuer à la réduction de l'empreinte environnementale des élevages.

En amont, les procédés qui interviennent dans l'élaboration des aliments pour bétail contribuent lourdement au poids environnemental des productions animales. Dans une approche globale, le choix des composants de la ration devraient également tenir compte des impacts liés aux phases initiales de leur fabrication. De même, une évaluation complète devra intégrer toutes les étapes suivant la phase d'élevage proprement dite. Les effets environnementaux du stockage, traitement et épandage des effluents devraient être considérés, tout comme les processus successifs qui aboutissent à la délivrance du produit final au consommateur, en y incluant d'autres facteurs comme les consommations énergétiques ou la qualité des eaux et des sols (méthodologie des analyses du cycle de vie).

Avec la croissance démographique mondiale et les changements dans les préférences alimentaires, la consommation de viande va augmenter fortement dans les années à venir. Dans un contexte de raréfaction des ressources et de pression sociétale grandissante, l'élevage est condamné à réduire son impact sur l'environnement. Ces enjeux pourraient néanmoins offrir des opportunités intéressantes pour le secteur en favorisant une meilleure efficience des moyens de production. La gestion raisonnée des intrants et des extrants permettra d'en préserver tout le potentiel nutritif et énergétique, assurant à l'agriculture un développement durable.

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