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Gaseous emissions during the fattening of pigs kept either on fully slatted floors or on straw flow

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The aim of this study was to compare the environmental impact of the straw-flow system for fattening pigs with the slatted-floor system by measuring pollutant gas emissions such as ammonia (NH_3), nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2), manure nitrogen (N) content and emissions of water vapour (H_2O). Three successive batches of 32 pigs were fattened. For each batch, pigs were allotted to two groups raised in separated rooms fitted either with a concrete totally slatted-floor system (0.75 m^2 per pig) or with a straw-flow system (0.79 m^2 per pig). With this last system, pigs were kept on a sloped floor, straw being provided daily at the top of the pen. Throughout the fattening period, about 34.4 kg of straw were supplied per pig. 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. Rooms were ventilated mechanically in order to maintain a constant ambient temperature. Once a month, the emissions of NH_3, N_2O, CH_4, CO_2 and H_2O were measured hourly for 6 consecutive days via infrared photoacoustic detection. Mean daily emissions per pig fattened on the slatted floor or on the sloped floor were, respectively, 4.98 and 13.31 g NH_3, 0.67 and 0.68 g N_2O, 15.2 and 8.88 g CH_4, 548 g and 406 g CO_2 equivalents, 1.61 and 1.77 kg CO_2 and 2.33 and 2.95 kg H_2O. Except for N_2O emissions, all the differences were statistically significant ($P < 0.001$). From the slatted-floor system, the amount of slurry removed per fattening period was on average 256 kg per pig. From the straw-flow system, solid manure amounted on average to 209 kg per pig and liquid manure to 53 kg per pig. The total N-content of the manure was 2.23 kg N per pig with the straw-flow system (solid and liquid manure) v. *3.26 kg N per pig for slurry from the slatted-floor system. This reduction of 30% observed with the sloped floor was mainly explained by the higher level of NH_3-N emissions.*

Keywords: ammonia, greenhouse gases, pigs, slatted floors, straw flow

Introduction

From the 1950s onwards in Western Europe, straw-bedded systems in pig production were progressively replaced by the slatted-floor system, mostly for economic reasons. But there has been a renewed interest in litter systems, as they are associated with improved welfare (Tuyttens, 2005), reduced odour nuisance (Kaufmann, 1997), a better brand image of livestock production and easier acceptance by the neighbourhood of new pig house establishments (Chevrant-Breton and Daridan, 2003).

Types of litter system are numerous. The most frequent substrate is straw, but sawdust, wood shavings or even paper are also used (Andersson, 1996). Litter may be regularly scraped, about twice a week, or may be accumulated under animals and removed after one or several animal batches (Ramonet and Dappello, 2003). Building costs are often reduced in comparison with conventional pig houses with a slurry pit underneath the pens (Nicks, 2004a). Nevertheless, bedded systems imply extra costs with large quantities of straw and a high demand for labour (Bruce, 1990; Nicks, 2004a).

In the 1990s, Bruce (1990) developed a new bedding 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

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for surface area, straw, labour and for manure storage, combined with the satisfying of pig behavioural requirements such as rooting, chewing and manipulation, thanks to the substrate (Bruce, 1990; Lyons *et al*., 1995). However, to date, there have been few data regarding the impact on the environment of the straw-flow system, especially in relation to manure nitrogen (N) content (which constitutes a limiting factor for manure land spreading) and emissions of pollutant gases such as ammonia (NH_3) and greenhouse gases.

NH_3 emissions contribute to the eutrophisation and acidification of soil and water (Degré *et al*., 2001). In addition, NH_3 is a toxic gas, which irritates the respiratory tract at concentrations exceeding 15 p.p.m. (Urbain, 1997).

The greenhouse gas emissions involved in livestock production are carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) (Degré *et al*., 2001; Nicks, 2004a). However, in the case of CO_2, agriculture is also a consumer via plant photosynthesis, and the contribution of CO_2 to the greenhouse effect is much less important than that of CH_4 and N_2O as regards their warming potentials, which 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.

Water vapour (H_2O) flow is an important criterion in designing ventilation systems. Under winter conditions, excessive indoor relative humidity may arise, especially with bedded systems that release more moisture (International Commission of Agricultural Engineering, 2002). Thus, determination of H_2O emission is a key factor in specifying ventilation rates in livestock buildings.

Therefore, the aim of this study was to compare the environmental impact of the welfare-friendly straw-flow system with the slatted-floor system for fattening pigs by measuring pollutant gas emissions such as NH_3, N_2O, CH_4 and CO_2, manure N content and emissions of H_2O.

Material and methods

Experimental rooms

Pigs were housed in two identical rooms, one arranged with a straw-flow system and another arranged with a concrete totally slatted floor. The experimental rooms had a 30 m^2 horizontal area and a volume of 103 m^3. The pens, one per room, had a capacity for 16 pigs with an available floor space of 0.75 m^2 per pig kept on the slatted floor and 0.79 m^2 per pig kept on straw.

The concrete straw-flow system used in this experiment (Figure 1) 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 3.0 m with a slope of 6%, separated by a step of 10 cm of a dunging area 1-m wide with a slope of 10%. Long straw was manually supplied daily at the top of the slope. The amount of straw used per fattening period was 550 kg, i.e. 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. Samples of liquid and solid manure were analysed in order to determine dry matter and N content (Kjeldahl method).

The void percentage of the slatted floor was 15.6%. The slurry pit was above the ground level and had a height of 0.45 m. Pigs accessed the pen via an inclined plane. Before each fattening period, about 500 l water was poured into the slurry pit in order to have a 4-cm layer. At the end of each fattening period, the slurry pit was emptied and the pen washed. Slurries from each batch were sampled and analysed in order to determine dry matter and N content (Kjeldahl method).

Ventilation was provided using an exhaust fan in each room and was automatically adapted in 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.

Animals and feeding

The pigs were cross-bred Piétrain × Belgian Landrace. Three successive batches were fattened for the experiment with two 16-pig groups kept simultaneously on each floor type. 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. Cereals represented about two-thirds of the diet and soya-bean meal about 20%. For the three successive replicates, crude protein content was constituted, respectively, of 18.1%, 18.1% and 16.7% for the growing meal and of 17.1%, 16.2% 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. Feed and water intakes and feed conversion ratio were determined per group. At the slaughterhouse, carcass weights were individually determined and lean yield percentages were measured using the CGM optical method (Capteur de Gras Maigre by Sydel, France).

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 Photoacoustic Multi-gas Monitor 1312 (Innova Air Tech

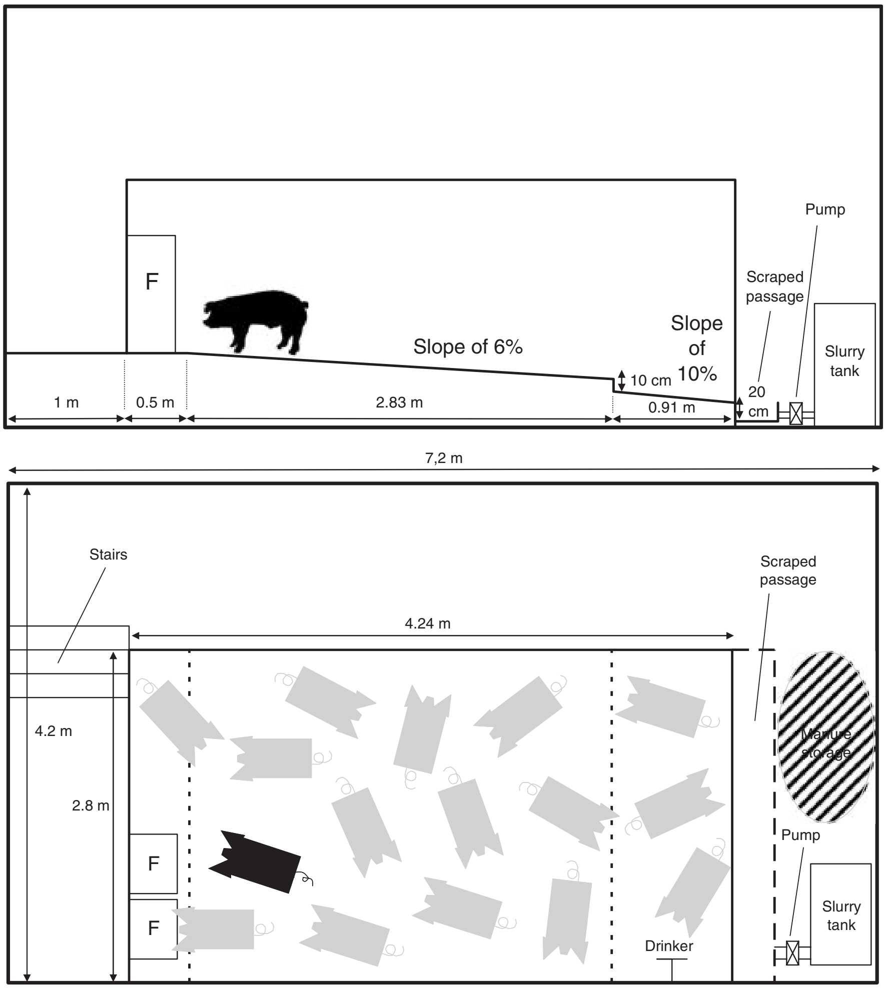

Figure 1 Plan of the room arranged with the straw flow system (F = feeder).

Instruments) equipped to measure NH_3, N_2O, CH_4, CO_2 and H_2O. The lower levels of detection were, respectively, 0.2 p.p.m. for NH_3, 0.03 p.p.m. for N_2O, 0.1 p.p.m. for CH_4 and 3.4 p.p.m. for CO_2, with an accuracy rate of 95%. 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. 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 using an electronic device (Exavent, Fancom®) and the hourly means were recorded. Emissions (E), expressed as mg/h, were calculated according to the following formula:

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

with D being the hourly mass flow (kg air per h); C_i and C_e being, respectively, the concentrations of gas in the air of the room and corridor (mg/kg dry air). The warming potential of the greenhouse gases, N_2O and CH_4 together, was expressed in CO_2 equivalents using the following equation:

$$\mathrm{EqCO_2}(\text{kg per pig per day}) = 23\,E_{CH_4} + 296\,E_{N_2O}, \qquad (2)$$

with E_{CH_4} and E_{N_2O} being the emissions of CH_4 and N_2O (kg per pig per day). CO_2 emissions were excluded from this estimation because this gas is also consumed by plant, which were integrated into the feed.

Statistical analysis

For each batch and for each gas, 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 (Statistical Analysis Systems Institute (SAS) 1999, software, proc MIXED): floor type (1 d.f.), period of measurements (3 d.f.) and interaction between floor type and period of measurements with 144 (24 h × 6 days) successive measurements per period. Residuals were assumed to be normally distributed, with a null expectation. The correlation between successive measurements was modelled using a type 1 autoregressive structure. The combined data obtained with the three batches were treated in the same way as for the previous analyses.

In order to compare the average daily gains, lean meat percentages and carcass values between the pigs kept on the two floor types, individual data regarding the pigs were tested using a generalised linear model (SAS (1999) software, proc GLM). In order to compare food conversions, water consumption and manure characteristics, data per pen from the three batches were used and tested using a Student t test (EXCEL® software, test.student).

Results

Climatic characteristics of the rooms

Table 1 presents temperatures and ventilation rates observed throughout the experiment. The difference between the temperatures measured in the two experimental rooms is related to the lower thermal leakage from the walls in the room with the slatted floor, which is linked to the location of the rooms in the building. Heat lost through the walls of the room with the slatted-floor system was at a lower level than that of the room with the straw-flow system and, as the heat loss level through the walls depends on the difference between the inside and the corridor temperatures (Δt), the effect on the temperature of the rooms was greater with the first batch (mean $\Delta t =$ 5.9°C) than with the two others (mean $\Delta t = 3.9$°C and 3.4°C, respectively). Concerning the difference between the mean inside temperature with batch 1 (18.8°C) and the two other batches (20.4°C), this was linked to the lower outside temperature during the period of the stay of the first batch. The lower ventilation rate observed with the first replicate can be explained by the lower temperature of the incoming air during this period.

Table 1 *Mean temperatures and ventilation rates observed in the experimental rooms during the fattening of three successive batches of pigs kept either on slatted floor or on straw flow*

	Batch			
	1	2	3	Mean ± s.d.[†]
Temperature (°C)				
Slatted floor	19.4	21.2	21.1	20.5 ± 1.0
Straw flow	18.1	19.5	19.9	19.1 ± 0.9
Service corridor	12.9	16.5	17.1	15.5 ± 2.3
Outside	0.9	11.8	11.8	8.1 ± 6.3
Ventilation rate (m^3/h per pig)				
Slatted floor	44.5	83.1	82.6	70.1 ± 22.1
Straw flow	36.5	66.3	84.9	62.6 ± 24.4

[†]Mean ± s.d. between batches.

Performance of the animals

The mean daily feed intake was 2.17±0.09 kg for pigs on the slatted floor and 2.24±0.05 kg for pigs on the sloped floor (mean±s.d. between batches). Taking into account the N content of the feed, the mean N intakes were 6.78, 6.91 and 6.78 kg per pig kept on the slatted floor and 7.12, 6.95 and 6.78 kg per pig kept on the sloped floor, for the three successive fattening periods. Table 2 presents the performance and carcass quality of pigs. Statistical analysis shows no difference between the pigs according to floor type.

Characteristics of the manure

The characteristics of the manure removed at the end of fattening periods are presented in Table 3. The amount of slurry obtained with the slatted-floor system was 10% greater than the total amount of manure from the straw-flow system (288 kg *v.* 262 kg) but the difference is not statistically significant. Without the amount of water poured into the slurry pit before the arrival of the animals and without the amount of straw provided with the straw-flow system, the amount of manure produced by the pigs

Table 2 *Performance during the fattening of three batches of pigs kept on slatted floor or on straw flow (mean ± s.d. between batches)*

	Slatted floor	Straw flow
No. of pigs	48	48
Initial weight (kg)	23.4 ± 1.8	23.3 ± 1.4
Final weight (kg)	110.2 ± 2.9	113.0 ± 4.9
Average daily weight gain (g per day)	733 ± 32	758 ± 45
Feed conversion ratio	3.0 ± 0.0	3.0 ± 0.1
Water consumption (l per pig per day)	4.1 ± 0.3	4.5 ± 0.1
Lean meat percentage (%)	59.2 ± 0.7	59.0 ± 1.7
Carcass value (Euro per kg live weight)	1.05 ± 0.03	1.06 ± 0.07

Table 3 *Characteristics of the manure removed at the end of the fattening periods (mean ± s.d. between batches)*

	Amount removed (kg per pig)	DM (g/kg)	Total N (g N per kg DM)	Total N (kg per pig)
Slatted floor				
Slurry[†]	288 ± 65	129 ± 14	89 ± 3	3.26 ± 0.48
Straw flow				
Solid manure[‡]	209 ± 13	259 ± 26	38 ± 7	1.92 ± 0.47
Liquid manure	53 ± 9	16 ± 4	351 ± 12	0.31 ± 0.10

Abbreviations: DM = dry matter; N = nitrogen.
[†]Slurry including water supplied in the pit before arrival of animals (about 31.3 l water per pig).
[‡]Solid manure including straw supplied throughout the fattening period (about 34 kg straw per pig).

Table 4 *Emissions (per pig and per day) of ammonia (NH_3), nitrous oxide (N_2O), methane (CH_4), carbon dioxide (CO_2), CO_2-equivalents (Eq_{CO_2}) and water vapour (H_2O) during fattening of three batches of pigs kept on slatted floor or on straw flow*

		Slatted floor	Straw flow	Significance†
Batch 1‡	NH_3 (g)	4.01 ± 3.08	12.01 ± 5.90	***
	N_2O (g)	0.37 ± 0.14	0.34 ± 0.19	NS
	CH_4 (g)	12.25 ± 6.78	7.49 ± 1.24	**
	Eq_{CO_2} (g)¶	391 ± 196	272 ± 82	**
	CO_2 (kg)	1.56 ± 0.55	1.74 ± 0.72	*
	H_2O (kg)	2.05 ± 0.82	2.82 ± 1.10	**
Batch 2‡	NH_3 (g)	5.61 ± 3.03	10.69 ± 5.18	**
	N_2O (g)	0.32 ± 0.07	0.25 ± 0.05	**
	CH_4 (g)	17.06 ± 6.59	9.83 ± 2.42	***
	Eq_{CO_2} (g)¶	488 ± 165	299 ± 70	***
	CO_2 (kg)	1.67 ± 0.35	1.69 ± 0.36	NS
	H_2O (kg)	2.53 ± 0.50	2.84 ± 0.46	NS
Batch 3‡	NH_3 (g)	5.30 ± 4.29	17.22 ± 10.55	***
	N_2O (g)	1.32 ± 1.21	1.46 ± 1.41	NS
	CH_4 (g)	16.28 ± 4.80	9.33 ± 1.82	***
	Eq_{CO_2} (g)¶	764 ± 459	646 ± 453	**
	CO_2 (kg)	1.60 ± 0.40	1.89 ± 0.57	**
	H_2O (kg)	2.40 ± 0.45	3.19 ± 0.73	**
Batches 1 to 3§	NH_3 (g)	4.98 ± 0.85	13.31 ± 3.45	***
	N_2O (g)	0.67 ± 0.56	0.68 ± 0.67	NS
	CH_4 (g)	15.2 ± 2.58	8.88 ± 1.23	***
	Eq_{CO_2} (g)¶	548 ± 194	406 ± 208	***
	CO_2 (kg)	1.61 ± 0.06	1.77 ± 0.11	***
	H_2O (kg)	2.33 ± 0.25	2.95 ± 0.21	***

†Significance: NS $P > 0.05$; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.
‡For each gas and each floor type, mean ± s.d. between the four periods of measurement.
§For each gas and each floor type, mean ± s.d. between the three batches.
¶Eq_{CO2} are warming potentials of greenhouse gases, N_2O and CH_4 together, expressed in CO_2-equivalents by the following equation: $Eq_{CO_2} = 296E_{N_2O} + 23E_{CH_4}$; with E_{N_2O} and E_{CH_4} being the emissions of N_2O and CH_4.

was 256 kg and 227 kg, respectively, and this difference was not significant.

Manure N content (kg per pig) was greater (almost +50%) with the slatted-floor system than with the straw-flow system ($P < 0.05$). With this last system, about one-fifth of the manure was in liquid form. The N content (per kg of dry matter) of liquid manure was close to 10 times greater than that of solid manure but represented just 14% of manure N produced by the pigs.

Gas emissions

Table 4 presents gas emissions observed during the fattening of the three batches. NH_3 emissions were 2.7 times greater when keeping pigs on the straw flow than on the slatted floor. N_2O emissions did not differ significantly according to floor type. CH_4 emissions were reduced by 40% with the straw flow. Therefore, emissions of CO_2 equivalents were decreased by 25% with the sloped system. CO_2 and H_2O emissions were greater in the straw-flow system, with +10% and +25%, respectively. Figure 2 shows the mean evolution of emissions throughout the fattening periods. Emissions increased regularly throughout the course of time, whatever the gas or the floor type. In comparison with the beginning, emissions at the end of the fattening period were about 5-fold for NH_3, 6.5-fold for N_2O and 2-fold for CH_4, CO_2 and H_2O.

Discussion

Performance of the animals

In this experiment, keeping fattening pigs on the slatted floor or on the straw-flow system did not induce a difference in performance or carcass quality. Results from the literature concerning this comparison are rare and contradictory, showing either a better (Lyons *et al.*, 1995) or worse (Andersson and Svendsen, 2001) performance for fattening pigs kept on straw flow. But in the latter study, other factors, such as differences in ambient temperature, could have contributed towards an explanation of the difference.

Nitrogen content of the manure

Manure N content (kg per pig) was significantly reduced with the straw-flow system, −30% for liquid and solid manure together, in comparison with slurry from the slatted-floor system. This implies that more N gaseous emissions occurred with the straw-flow system. These

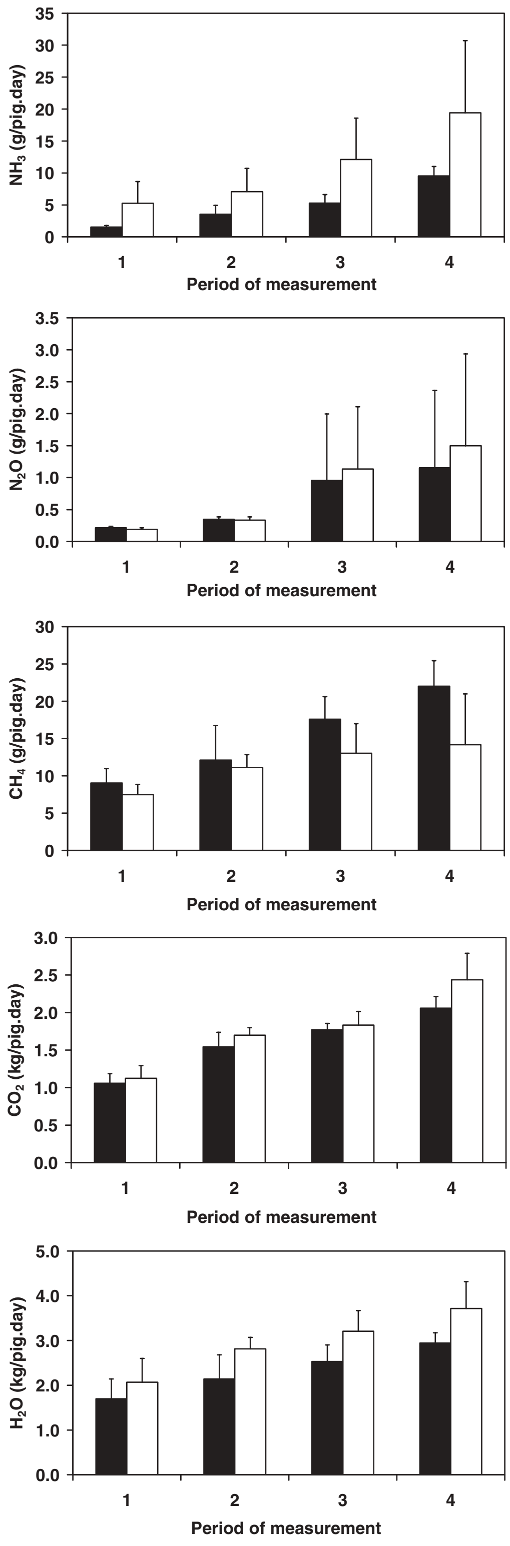

Figure 2 Evolution of emissions of ammonia (NH_3), nitrous oxide (N_2O), methane (CH_4), carbon dioxide (CO_2) and water vapour (H_2O) throughout fattening period of pigs kept on slatted floor (closed bars) or on straw flow (open bars). For each period of measurement, emission rates are means with s.d. between the values from three batches.

emissions may occur in the form of NO, N_2O, NH_3 and N_2 (Groenestein and Van Faassen, 1996). In this study, the difference between the N-NH_3 emissions of the two systems, i.e. 0.823 kg (1.315 kg with straw flow *v.* 0.492 kg with the slatted floor with a 120-day fattening period), can explain 80% of the difference in the manure N content, i.e. 1.03 kg. The remainder could be due to N_2 or NO emissions from the heap of solid manure in the room with the straw-flow system. When comparing manure N-content of deep litter and slurry systems for fattening pigs, the lower N-content of the deep litter was attributed mainly to N_2 emissions from the litter (Nicks, 2004b).

Gas emissions

In this study, NH_3 emissions from the room with the slatted floor were at a relatively low level according to values reported in the literature, which range from 4 to 14 g per pig per day (Groot Koerkamp *et al.*, 1998; Robin *et al.*, 1998; Fernandez *et al.*, 1999; Nicholson *et al.*, 2000; Hornig *et al.*, 2001). Water supplied in the slurry pit before the arrival of the animals and the cleanliness of the slatted floor and the pigs may explain our low values for this floor type. Water supplied in the slurry pit is also a practical recommendation to lower the olfactory nuisance of the slurry.

NH_3 emissions from straw flow pens have been very rarely studied. Amon *et al.* (2005) present preliminary results with values ranging from 2 to 10 g per pig per day throughout the fattening period. Emissions observed in the current study are greater, with a mean value of 13.3 g per pig per day. These results are close to the values obtained by Hornig *et al.* (2001), who compared the two floor types and found emission rates from 4.7 to 5.9 g NH_3 per pig per day kept on slatted floor and from 7.2 to 11.5 g NH_3 per pig per day kept on straw-flow system. Therefore, these results would confirm that emissions from the straw-flow system are higher than from the slatted-floor system.

NH_3 emissions come principally from the microbial degradation of urea by enzyme urease, which is abundant in faeces (Muck and Steenhuis, 1981). In this study, with the straw-flow system, it was expected that separation of liquid manure associated with storage in a hermetic tank would have decreased the release of NH_3. Nevertheless, emissions were higher than from slurry. The experiments of Elzing and Monteny (1997) and Braam and Swierstra (1999) showed that the development of urease activity on a concrete floor is quick, with the volatilisation peak being 2 to 3 h after application of urine samples. Groenestein *et al.* (2006) observed higher emissions from fouled concrete floor than from slurry pit. Thus, in the current experiment, the separation of liquid and solid fractions of manure unquestionably 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).

N_2O emissions did not differ with the floor type. The formation of N_2O occurs during incomplete nitrification/denitrification processes performed by bacteria in manure (Groenestein and Van Faassen, 1996). N_2O is mainly synthesised during denitrification, in case of presence of oxygen and/or low availability of degradable carbohydrates (Poth and Focht, 1985). During nitrification, N_2O can also be synthesised where there is a lack of oxygen and/or nitrite accumulation (Groenestein and Van Faassen, 1996; Degré *et al*., 2001; Veeken *et al*., 2002). 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) but not in slurry. Release from pig houses with slatted floor is usually considered as negligible. However, emissions can occur from manure presented on the floor and these have been evaluated by Kermarrec (1999) at 0.75 g N_2O per pig per day, a value close to our own results. For pigs kept on sloped floor, Amon *et al*. (2005) obtained daily emissions from 0.06 to 0.30 g N_2O per pig (preliminary results), values lower than those in this study.

Studies concerning CH_4 emissions from pig houses with slatted floor have shown emissions ranging from 2 to 30 g CH_4 per pig per day (Groot Koerkamp and Uenk, 1997; Hornig *et al*., 2001; European Commission, 2003; Gallmann *et al*., 2003; Godbout *et al*., 2003; Guarino *et al*., 2003; Haeussermann *et al*., 2006). Variations originated from the kind of slatted floor (totally or partly), the ventilation system (natural or controlled) and the season. With the straw-flow system, results have ranged from 4 g CH_4 per pig per day (Amon *et al*., 2005) to 20 g CH_4 per pig per day (Hornig *et al*., 2001). Emission rates observed in the current experiment are in between, with 15.2 and 8.88 g CH_4 per pig per day with the slatted-floor system and the straw-flow system, respectively. CH_4 from pig houses has two origins: enteric fermentation and release from manure (Degré *et al*., 2001). Production in the digestive tract is a function of ingested carbon and is estimated to be about 3 g CH_4 per pig per day (Texier, 1997). CH_4 synthesis in the manure occurs under exclusive anaerobic conditions (Hellmann *et al*., 1997), which are met in the slurry. Methanogenesis is enhanced with high temperature, low pH and increased biodegradability of the manure (Monteny *et al*., 2006). Moreover, emptying and cleaning the slurry pits between batches contributes to an important decrease in CH_4 emissions during the first weeks of the fattening period (Haeussermann *et al*., 2006). However, in this study, the mean emission after the third week of fattening was already 50% of the emission at the end of the fattening period but, compared with the results of Haeussermann *et al*. (2006), the total slurry production was about 50% lower with a high dry matter content (12.9%), a factor interfering with methanogenesis. In litter, CH_4 formation is negatively correlated with aeration rate. So, an increase in the amount of straw, which favours aeration, impairs CH_4 formation (Sommer and Møller, 2000; Chadwick, 2005). Therefore, in the straw-flow system, despite high manure temperature, aeration due to the heap's physical structure and daily manual scraping may explain the lower emissions, as previously observed by Hornig *et al*. (2001).

Warming potential was significantly lower with the sloped system, with −25% in comparison with the slatted system. It has to be noted that CO_2 emissions are not included in this calculation, which is only based on N_2O and CH_4 emissions, because agriculture is also a consumer of CO_2. Moreover, this estimation does not take into account heating energy, ventilation energy or energy involved in removing manure. Nevertheless, it is interesting to note that more greenhouse gases are emitted during the housing of fattening pigs on the slatted-floor system. The difference is due to the greater CH_4 release with this conventional system.

The majority of the CO_2 in the air of pig houses comes from animal respiration. CO_2 exhalation is estimated to be about 1.5 to 1.7 kg/day for a 65-kg pig (Ni *et al*., 1999a; International Commission of Agricultural Engineering, 2002). However, release from manure is not negligible, as observed by Ni *et al*. (1999b), on the slatted floor with 0.54 kg CO_2 per pig per day and by Jeppsson (2000) on deep litter with 0.46 kg CO_2 per pig per day. In the current experiment, the total emission of the straw-flow system was about 10% higher than the emission from the slurry system.

Like CH_4 and CO_2, H_2O has two sources: animals and manure. The International Commission of Agricultural Engineering (2002) estimated production at house level to be about 2.7 kg for a 65-kg pig kept on partly slatted floor with a room temperature of 20.5°C. Our results on fully slatted floor are lower, with 2.33 kg H_2O per pig per day. 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 mainly from animals. By contrast, with bedded systems, emissions from litter should not be neglected. Indeed, water evaporation from litter is enhanced by high temperature due to fermentation inside the manure (Nicks *et al*., 1994). With straw-based deep litter, authors have presented emissions ranging from 2.7 to 5.2 kg H_2O per pig per day (Robin *et al*., 1999; Jeppsson, 2000; Nicks *et al*., 2004). With the straw-flow system, although liquid manure was stored in a hermetic tank, evaporation from manure can explain greater emissions than with the slatted-floor system. Moreover, extra water consumption (+10%) of pigs kept on the sloped floor in this study may have contributed to the phenomenon. Therefore, with the straw-flow system, higher ventilation rates are consequently needed in 'winter conditions' when air relative humidity is the key factor in determining the ventilation rate.

The increase in the emissions of the five gases during the fattening periods shows the necessity for sampling air regularly during the whole period in order to obtain an accurate measurement of these emissions.

Conclusion

The amount of manure obtained was slightly lower (but not significantly so) with the sloped system, for which about one-fifth of the manure was in the liquid form and the rest in the litter form. Manure N content (kg per pig) was also reduced with this kind of floor in comparison with the slatted floor. Greater NH_3 emissions mainly explained this result. The impact on global warming was greater for the slatted-floor system, which showed equal emissions of N_2O but greater CH_4 emissions. The release of H_2O was at a higher level from the straw-flow system. Performance and carcass quality did not differ according to floor type.

In conclusion, the environmental assessment of the raising of fattening pigs on the welfare-friendly straw-flow system seems to conflict with lower manure N content and lower greenhouse gas emissions but higher NH_3 emissions in comparison with the conventional slatted-floor system.

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References

Amon B, Pöllinger A, Kryvoruchko V, Mösenbacher I, Hausleitner A and Amon T 2005. Ammonia and greenhouse gas emissions from a straw flow system for fattening pigs. In Proceedings of the 11th International Conference on the FAO ESCORENA Network on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture (ed. P Bernal, R Moral, R Clemente and C Paredes), pp. 273–276. FAO, Murcia, Spain.

Andersson M 1996. Performance of bedding materials in affecting ammonia emissions from pig manure. Journal of Agricultural Engineering Research 65, 213–222.

Andersson M and Svendsen J 2001. Pens with sloped flooring in an uninsulated growing-finishing house. Department of Agricultural Biosystems and Technology, Swedish University of Agricultural Science, Alnarp, Sweden.

Braam CR and Swierstra D 1999. Volatilization of ammonia from dairy housing floors with different surface characteristics. Journal of Agricultural Engineering Research 72, 59–69.

Bruce JM 1990. Straw-Flow: a high welfare system for pigs. Farm Building Progress 102, 9–13.

Chadwick DR 2005. Emissions of ammonia, nitrous oxide and methane from cattle manure heaps: effect of compaction and covering. Atmospheric Environment 39, 787–799.

Chevrant-Breton A and Daridan D 2003. Conditions de développement des élevages de porcs en France. Analyse de 611 projets déposés entre 1997 et 2001. In 35èmes journées de la recherche porcine en France (ed. Institut Technique du Porc), pp. 189–195. Institut Technique du Porc, Paris, France.

De Oliveira PAV, Souloumiac D, Robin P and Kermarrec C 1999. Comparaison des productions de chaleurs en engraissement de porcs sur litière de sciure ou sur caillebotis intégral. Annales de Zootechnie 48, 117–129.

Degré A, Verhève D and Debouche C 2001. Emissions gazeuses en élevage porcin et modes de réduction: revue bibliographique. Biotechnology, Agronomy, Society and Environment 5, 135–143.

Elzing A and Monteny GJ 1997. Modelling and experimental determination of ammonia emission rates from a scale model dairy-cow house. Transactions of the American Society of Agricultural Engineers 40, 721–726.

European Commission, 2003. IPPC. Reference document on BAT for intensive rearing poultry and pigs. Retrieved January 4, 2006, from http://www.epa.ie/Licensing/IPPCLicensing/BREFDocuments.

Fernandez JA, Poulsen HD, Boisen S and Rom HB 1999. Nitrogen and phosphorus consumption, utilisation and losses in pig production: Denmark. Livestock Production Science 58, 225–242.

Gallmann E, Hartung E and Jungbluth T 2003. Long-term study regarding the emission rates of ammonia and greenhouse gases from different housing systems for fattening pigs – final results. In Proceedings of the International Symposium on Gaseous and Odour Emissions from Animal Production Facilities (ed. Commission Internationale du Génie Rural), pp. 122–130. Danish Institute for Agricultural Sciences, Foulum, Denmark.

Gibbs PA, Parkinson RJ, Misselbrook TH and Burchett S 2002. Environmental impact of cattle manure composting. In Microbiology of composting (ed. H Insam, N Riddech and S Klammer), pp. 446–456. Springer, New York, USA.

Godbout S, Lague C, Lemay SP, Marquis A and Fonstad TA 2003. Greenhouse gas and odour emissions from swine operations under liquid manure management in Canada. In Proceedings of the International Symposium on Gaseous and Odour Emissions from Animal Production Facilities (ed. Commission Internationale du Génie Rural), pp. 426–443. Danish Institute for Agricultural Sciences, Foulum, Denmark.

Groenestein CM and Van Faassen 1996. Volatilization of ammonia, nitrous oxide and nitric oxide in deep-litter systems for fattening pigs. Journal of Agricultural Engineering Research 65, 269–274.

Groenestein CM, Den Hartog LA and Metz JHM 2006. Potential ammonia emissions from straw bedding, slurry pit and concrete floors in a group-housing system for sows. Biosystems Engineering 95, 235–243.

Groot Koerkamp PWG and Uenk GH 1997. Climatic conditions and aerial pollutants in and emissions from commercial animal production systems in the Netherlands. In Proceedings of the International Symposium on Ammonia and Odour Control from Animal Production Facilities (ed. JAM Voermans and GJ Monteny), pp. 139–144. Dutch Society of Agricultural Engineering, Rosmalen, The Netherlands.

Groot Koerkamp PWG, Metz JHM, Uenk GH, Philips VR, Holden MR, Sneath RW, Short JL, White RP, Hartung J, Seedorf J, Schröder M, Linkert KH, Pedersen S, Takai H, Johnsen JO and Wathes CM 1998. Concentrations and emissions of ammonia in livestock buildings in Northern Europe. Journal of Agricultural Engineering Research 70, 79–95.

Guarino M, Fabbri C, Navarotto P, Valli L, Mascatelli G, Rossetti M and Mazzotta V 2003. Ammonia, methane and nitrous oxide emissions and particulate matter concentrations in two different buildings for fattening pigs. In Proceedings of the International Symposium on Gaseous and Odour Emissions from Animal Production Facilities (ed. Commission Internationale du Génie Rural), pp. 140–149. Danish Institute for Agricultural Sciences, Foulum, Denmark.

Haeussermann A, Hartung E, Gallmann E and Jungbluth T 2006. Influence of season, ventilation strategy and slurry removal on methane emissions from pig houses. Agriculture, Ecosystems and Environment 112, 115–121.

Hellmann B, Zelles L, Palojärvi A and Bai Q 1997. Emission of climate-relevant trace gases and succession of microbial communities during open-windrow composting. Applied and Environmental Microbiology 63, 1011–1018.

Hornig G, Stollberg U, Fenyvesi L and Matyas L 2001. Environmentally relevant emissions from modernized fattening pig houses in Hungary. In Proceedings of the Ninth International Conference on the FAO ESCORENA Network on Recycling of Agricultural, Municipal and Industrial Residues in Agriculture (ed. F Sangiorgi), pp. 127–132. FAO, Milan, Italy.

Intergovernmental Panel on Climate Change 2001. Climate change 2001: the scientific basis. Cambridge University Press, New York, USA.

International Commission of Agricultural Engineering 2002. Fourth report of working group on climatization of animal houses. Heat and moisture production at animal and house levels. Danish Institute of Agricultural Sciences, Horsens, Denmark.

Jeppsson KH 2000. Carbon dioxide emission and water evaporation from deep litter systems. Journal of Agricultural Engineering Research 77, 429–440.

Kaufmann R 1997. Litière biomaîtrisée pour porc à l'engrais: amélioration de la technique et valorisation des données importantes pour l'environnement. In 29èmes journées de la recherche porcine en France (ed. Institut Technique du Porc), pp. 311–318. Institut Technique du Porc, Paris, France.

Kermarrec C, 1999. Bilan et transformations de l'azote en élevage intensif de porcs sur litière. PhD thesis, University of Rennes, France.

Lyons CAP, Bruce JM, Fowler VR and English PR 1995. A comparison of productivity and welfare of growing pigs in four intensive systems. Livestock Production Science 43, 265–274.

Monteny GJ, Bannink A and Chadwick D 2006. Greenhouse gas abatement strategies for animal husbandry. Agriculture, Ecosystems and Environment 112, 163–170.

Muck RE and Steenhuis TS 1981. Nitrogen losses in free stall dairy barns. In Livestock waste: a renewable source. In Proceeding of the Fourth International Symposium on Livestock Wastes (ed. American Society of Agricultural Engineering), pp. 406–409. American Society of Agricultural Engineering, St Joseph, Michigan, USA.

Ni JQ, Hendriks J, Coenegrachts J and Vinckier C 1999a. Production of carbon dioxide in a fattening pig house under field conditions. I: Exhalation by pigs. Atmospheric Environment 33, 3691–3696.

Ni JQ, Vinckier C, Hendriks J and Coenegrachts J 1999b. Production of carbon dioxide in a fattening pig house under field conditions. II: Release from the manure. Atmospheric Environment 33, 3697–3703.

Nicholson FA, Williams JR and Chambers BJ 2000. Ammonia losses from straw and slurry based manure management systems. In Air pollution from agricultural operations. Proceedings of the Second International Conference (ed. American Society of Agricultural Engineers), pp. 18–24. American Society of Agricultural Engineers, Des Moines, Iowa, USA.

Nicks B 2004a. Aspects environnementaux et zootechniques de l'élevage de porcs charcutiers et de porcelets sevrés sur litières accumulées de paille ou de sciure. PhD thesis, University of Liège, Belgium.

Nicks B 2004b. Caractéristiques techniques et aspects environnementaux de l'élevage de porcs charcutiers et de porcelets sevrés sur litières accumulées. Annales de Médecine Vétérinaire 148, 31–38.

Nicks B, Marlier D and Canart B 1994. Comparaison des températures de litières et des niveaux de pollution de l'air lors d'engraissement de porcs sur litières biomaîtrisées à base de sciure ou de paille hachée. In 26èmes journées de la recherche porcine en France (ed. Institut Technique du Porc), pp. 85–90. Institut Technique du Porc, Paris, France.

Nicks B, Laitat M, Farnir F, Vandenheede M, Désiron A, Verhaeghe C and Canart B 2004. Gaseous emissions from deep-litter pens with straw or sawdust for fattening pigs. Animal Science 78, 99–107.

Poth M and Focht DD 1985. ^{15}N kinetic analysis of N_2O production by *Nitrosomonas europaea*: an examination of nitrifier denitrification. Applied and Environmental Microbiology 49, 1134–1141.

Ramonet Y and Dappello C 2003. L'élevage des porcs sur litière: une diversité de systèmes en engraissement. In 35èmes journées de la recherche porcine en France (ed. Institut Technique du Porc), pp. 1–6. Institut Technique du Porc, Paris, France.

Robin P, De Oliveira PA, Souloumiac D, Kermarrec C and Dourmad JY 1998. Effect of housing system, litter Versus totally slatted floor, on mass balances of water, nitrogen, and phosphorus in growing-finishing pigs. In Report of the eighth international conference of the European cooperative research network on recycling of agricultural municipal and industrial residuals in agriculture (ed. J Martinez and MN Maudet), pp. 71–77. FAO, Rennes, France.

Robin P, De Oliveira PA and Kermarrec C 1999. Productions d'ammoniac, de protoxyde d'azote et d'eau par différentes litières de porcs durant la phase de croissance. In 31èmes journées de la recherche porcine en France (ed. Institut Technique du Porc), pp. 111–115. Institut Technique du Porc, Paris, France.

Sommer SG and Møller HB 2000. Emission of greenhouse gases during composting of deep litter from pig production – effect of straw content. Journal of Agricultural Science, Cambridge 134, 327–335.

Statistical Analysis Systems Institute 1999. SAS/STAT user's guide: statistics (version 8). SAS Inst. Inc., Cary, NC, USA.

Texier C 1997. Elevage porcin et environnement. Institut Technique du Porc, Paris, France.

Tuyttens FAM 2005. The importance of straw for pig and cattle welfare: a review. Applied Animal Behaviour Science 92, 261–282.

Urbain B, 1997. Toxicité de l'ammoniac pour l'appareil respiratoire du porc. PhD thesis, University of Liège, Belgium.

Veeken A, De Wilde V and Hamelers B 2002. Passively aerated composting of straw-rich pig manure: effect of compost bed porosity. Compost Science and Utilization 10, 114–128.