Influence of environmental factors and the addition of wood shavings on ammonia and odour emissions from fresh livestock manure

N. M. Ngwabie, K.-H. Jeppsson, G. Gustafsson, S. Nimmermark
Swedish University of Agricultural Sciences, Department of Rural Buildings and Animal Husbandry, P.O. Box 86, S-230 53 Alnarp, Sweden
Ngwa.Martin.Ngwabie@ltj.slu.se

ABSTRACT

Gaseous emissions from livestock manure may adversely affect human and animal health as well as the surrounding environment. In an effort to understand and mitigate these emissions, the effects of different environmental factors and the addition of wood shavings on ammonia and odour emissions from fresh pig and dairy cow manure were studied. The manure was divided into two portions and wood shavings (25% pine and 75% spruce) were mixed with one portion. Emissions from equal volumes (0.009 m^3) of both portions were measured at different environmental conditions in a flux chamber. The manure temperature was varied between 15–30 °C. Fresh air at temperatures between 16–26 °C was passed at a fixed rate over the manure. The addition of wood shavings decreased the total-N and NH_4^+-N, but increased the pH of the manure at the end of the experiment. The temperature of the manure with wood shavings increased faster than that of the manure without wood shavings. The ammonia emission from the pig manure (0.08–0.41 mg m^{-2} s^{-1}) was on average much higher than the ammonia emission from the cow manure (0–0.08 mg m^{-2} s^{-1}). The odour emission from the pig manure was high (21–930 OU m^{-2} s^{-1}), and significantly higher than the odour emission from the cow manure (1–6 OU m^{-2} s^{-1}). A positive correlation was found between the ammonia emissions and the manure temperature. Ammonia emissions were about 2 times higher at manure temperatures of about 25 °C compared to emissions at about 15 °C. Odour emissions were positively correlated with the temperature of cow manure. Ammonia emissions at 25 °C were high, while odour emissions at 25 °C were lower than those at 20 °C for the pig manure with wood shavings. The emissions from the cow manure but not from the pig manure were positively correlated to the water vapour pressure. The measurements indicated a positive correlation between ammonia and odour emissions for the cow manure as well as for the pig manure without wood shavings. The addition of wood shavings to animal manure does not seem to automatically mitigate ammonia or odour emissions as it also affects the temperature and the pH.

Keywords: Dry matter, C/N ratio, volatilization, temperature, ammonium, Sweden.

1. INTRODUCTION

Ammonia, greenhouse gases and odour emissions are major environmental problems related to animal production. Agriculture contributes significantly to the anthropogenic emissions of ammonia and greenhouse gases (Jungbluth et al. 2001; FAO 2006). Estimates suggest that livestock buildings, manure storage, manure spreading and animal grazing account for a major part of ammonia emissions into the atmosphere (Statistics-Sweden 2007). Odour from animal production facilities originating from a large number of released odorants may negatively influence residents in the surrounding neighbourhood (Nimmermark 2004; Schiffman et al.

2001). In animal production, faeces and urine are major sources of ammonia and odour. Mitigation strategies include air cleaning technologies (Luo and Lindsey 2006; Verdoes and Zonderland 1999) and methods for reduction of the gas release such as improvements in manure handling and feed manipulation (Hayes et al. 2004; Kai et al. 2008; Le et al. 2005). It has been suggested that reduction measures should deal primarily with housing, manure handling, feed (for example protein content and feed additives) and management systems (Hartung 1992).

Gaseous emissions are affected by environmental, biological, chemical and physical factors. Factors considered important for the generation and release of gaseous emissions include 1) environmental factors: temperature, air exchange rate and air speed above manure surface; 2) manure characteristics: dry matter (DM) content, carbon-to-nitrogen (C/N) ratio and pH; 3) factors related to management: feed composition, manure storage time inside the barn and the size of manure surface (Andersson 1995; Gustafsson 1996). A comparatively new study suggests that in addition to temperature, the air humidity (water vapour pressure) is also important for ammonia and odour release (Nimmermark and Gustafsson 2005).

With regards to temperature, ammonia production from urea hydrolysis to the subsequent processes of dissociation and volatilisation is faster at higher temperatures (Groot Koerkamp 1994; Monteny and Erisman 1998). Odour emissions have also been reported to increase with temperature (Le et al. 2005).

The use of straw, wood shavings, peat or other materials as bedding for animals provides a resting surface and rooting or scratching material. Such materials also adsorb urine and manure. The type and quantity of material affects gaseous emissions in the building. The addition of these materials to manure increase the DM content and the C/N ratio thereby providing energy for microbes to immobilise excess ammonium leading to reduced ammonia emissions (Groenestein and Van Faassen 1996; Poincelot 1974). The addition of straw to farmyard manure has also been shown to reduce methane and nitrous oxide emissions (Yamulki 2006). However, depending on the design and management, systems with bedding materials may emit more ammonia than systems without bedding materials. This could be due to manure accumulation on the surface of the bedding material which can continue to emit ammonia for a longer period of time. Systems without bedding materials may have slatted floors through which the manure drops into the slurry pit and might not be affected by air flow in the building (Sommer et al. 2006). More ammonia and greenhouse gases were emitted in a system where pigs were reared on straw based deep litter than in a system where the pigs were kept on fully slatted floor (Philippe et al. 2007). Microbial activities during the degradation of the manure may result in changes in the pH and heat release which indirectly affect gaseous emissions. Ammonia emissions may be greater from solid than from liquid manure during the initial phase of microbial degradation due to a higher self-heating temperature resulting from microbial activities in the solid manure (Dewes, 1999).

An effective mitigation strategy should consider all forms of gaseous emissions to avoid the problem of pollution swapping. It is undesirable if the mitigation of ammonia results to increased odour production from animal husbandry. An inconsistent pattern has been reported in the relationship between ammonia and odour concentrations when measurements were carried out in buildings with low ammonia concentrations and in laboratory reactors (Ogink and Koerkamp 2001; Fakhoury et al. 2000). Mitigation methods should be cost efficient and it is of great interest if considerable reductions of gas emissions can be achieved inside barns by manipulating the indoor climate. In order to better understand and to improve the knowledge of ways to mitigate emissions by manipulation of the environment in animal production facilities with frequent manure removal, experiments were conducted with fresh manure under different environmental, physical and chemical conditions. Bedding materials like wood shavings which are mainly used for animal welfare reasons may significantly affect gas emissions in animal buildings. Given the limited knowledge that exists, it is interesting to study how the mixing of manure with wood shavings influence both gas and odour release.

1.2 Objective

The aim of this research was to identify how environmental factors and the addition of wood shavings influence the emission of gaseous compounds and odour from fresh livestock manure. Ammonia and odour emissions from fresh manure with and without the addition of wood shavings were to be compared in a laboratory experiment using a climate controlled chamber. The temperatures of the air and the manure were to be input parameters. The emissions of carbon dioxide, methane and nitrous oxide were also to be measured. Furthermore, the existence of a relationship between odour and ammonia emissions was to be studied.

2. MATERIALS AND METHODS

2.1 Manure collection and sample treatment

Manure was collected from the pit underneath the slatted floor in a building with fattening pigs. It was considered fresh since the pit was emptied daily to an external storage tank. Manure was also collected from a tie-stall dairy cow barn. It was collected from an open shallow slurry channel behind the cows where it was scraped out twice a day for storage.

The pigs from which the manure was collected were fed with crushed pellets (Piggfor, Origo 522) manufactured by Lantmännen Lantbruk® (Linköping, Sweden). It contained 129 g/kg crude protein and 12.4 MJ kg^{-1} metabolisable energy. The dairy cows from which manure was collected were fed with grass silage (20% clover and 80% grass) which was supplemented with a concentrate (50% grain and 50% commercial concentrate). The cows were of the breed Swedish Holstein and the milk production rate was about 9000 kg milk cow^{-1} yr^{-1} which is close to the Swedish average.

The experimental design is shown in Table 1. Fresh manure was collected three times on three different days (samples 1, 2 and 3) from each animal building. Each manure sample was divided into two portions and wood shavings were mixed with one portion. The mass ratio of manure to wood shavings was about 13:1 for the pig manure and 12:1 for the cow manure. The wood shavings were a combination of flakes from 40–60 years old pine (25%) and spruce (75%) trees. The flakes had a main particle size of 1–20 mm and were mostly 0.1–0.5 mm thick with some measuring up to 1 mm. Emissions from each portion were measured in a flux chamber for combinations of three different manure temperatures; approximately 15, 20 and 25 ^{o}C and three different air temperatures; approximately 15, 20 and 25 ^{o}C (Table 1). Each sample had 18 treatments, (9 without and 9 with wood shavings) giving a total of 54 treatments per animal manure type.

The time order for measurements of emissions from different treatments and for different manure temperatures and different air temperatures were randomly chosen in order to avoid systematic errors. The cow manure was analysed within 4 days and the pig manure within about 5 days after the manure samples were collected. Plastic papers were placed over the containers with the manure samples at the end of each day experiments were conducted. The samples were stored at room conditions (10–15 °C) in the building where the experiments were conducted.

Table 1. Experimental design for each animal manure type

	Manure without wood shavings					Manure with wood shavings				
			MT, °C					MT, °C		
			15	20	25			15	20	25
Sample 1, 2 or 3	AT, °C	15	Gases Odour	"	"	AT, °C	15	Gases Odour	"	"
		20	"	Gases Odour	"		20	"	Gases Odour	"
		25	"	"	Gases Odour		25	"	"	Gases Odour

AT: Air temperature, MT: Manure temperature, ": Gases and odour emissions were measured, Gases: NH_3, CH_4, N_2O and CO_2. Samples 2 and 3 were repetitions of the design in sample 1 with newly collected manure.

2.2 Experimental set-up

The design of the insulated laboratory climate chamber used in the experiment is shown in Figure 1. The manure sample was placed in a container (surface area 0.20 m^2) which was lowered into a water-bath. The height of the manure layer was 0.04–0.05 m. Manure temperatures (approximately 15, 20 or 25 °C) were attained by heating the water. A closed chamber was achieved by placing an insulated hood on top of the manure container. The chamber was approximately 0.55 m long and 0.37 m wide. The height from the manure surface up to the inner surface of the hood was approximately 0.57 m. The ventilated hood was equipped with an inlet duct, an exhaust fan connected to an outlet and a circulation fan for mixing the air inside the hood. The diameter of the inlet and outlet ducts was 0.07 m.

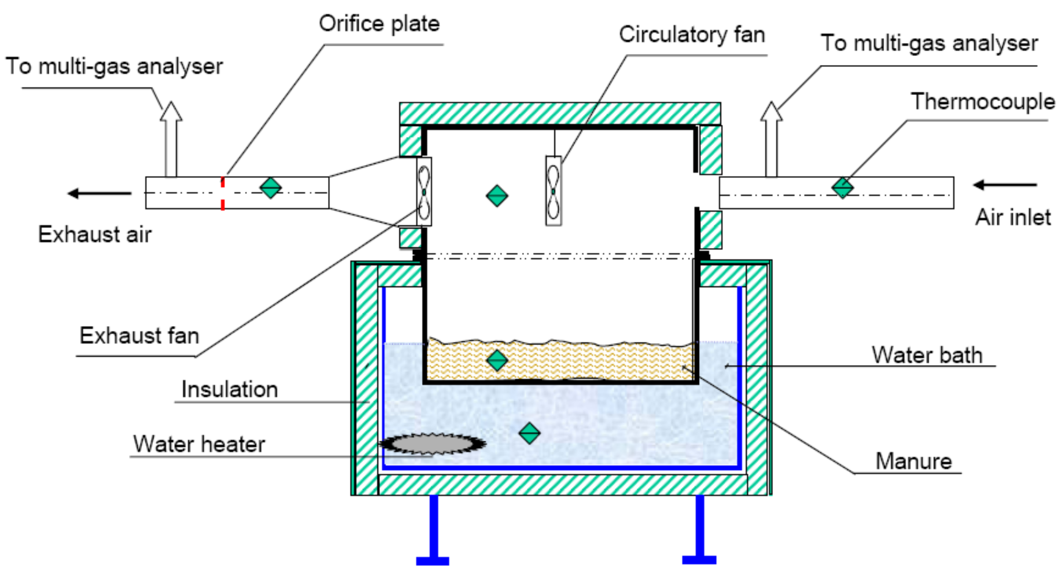

Figure 1. Design of the climate chamber and experimental set-up

Fresh air from a location outside the building was pulled through the chamber by the exhaust fan. The outside air was heated before entering the climate chamber in order to achieve specific air temperatures inside the chamber (approximately 15, 20 or 25 °C). The airflow rate through the chamber was kept fixed for each animal manure type by adjusting the voltage to the exhaust fan. It was calculated from the pressure difference that was measured at an orifice plate at the air exhaust duct. The pressure difference was measured with a pressure gauge (EMA 84, Halstrup-Walcher GmBh, Kirchzarten, Germany) with an accuracy of ±1 Pa. A lower airflow was used for the cow manure to ensure that the lower gas concentrations were measured. The airflow rate was 113±2 m^3 m^{-2} h^{-1} for the pig manure and 80±2 m^3 m^{-2} h^{-1} for the cow manure.

2.2.1 Measurements of gaseous emissions

The concentrations of NH_3 and also CH_4, N_2O, CO_2 and water vapour in the air were measured with a photoacoustic multi-gas analyser 1412 and a multiplexer 1309 (Lumasense Technologies SA, Ballerup, Denmark). The detection thresholds of the gases were: 0.2 ppm NH_3, 0.03 ppm N_2O, 0.4 ppm CH_4 and 1.5 ppm CO_2. The measuring accuracy for the multi-gas analyser according to data sheets from the manufacturer is within ±2–3% of the actual concentration.

Air was drawn through two channels of the multiplexer to the analyser using 3.2 mm (inner diameter) polytetrafluoroethylene (PTFE) tubes. The inlets of the tubes had 1 µm membrane filters (Millipore Corporation, Billerica, USA) that trapped dust particles. The background gas concentrations at the air inlet to the climate chamber were measured through one of the multiplexer channels for about an hour. This was carried out at the beginning and at the end of each day experiments were conducted. The multiplexer was on other occasions switched to a second channel where gas concentrations at the air exhaust were measured. The concentration of a gas at the exhaust was measured for about 30 minutes during which time it changed steadily before stabilising.

The emission rate of a gas was calculated using the measured airflow rate and the relative concentration of the gas as given in Eq. (1).

$$ER = VR(C_{exhaust} - C_{inlet}) \quad (1)$$

where ER is the emission rate in mg m^{-2} s^{-1}, VR is the ventilation rate in m^3 m^{-2} s^{-1}, $C_{exhaust}$ is the gas concentration in mg m^{-3} at the exhaust of the chamber, C_{inlet} is the gas concentration measured in mg m^{-3} at the inlet to the chamber. This was the mean for about 5 minutes of measurements after stabilisation.

2.2.2 Measuring the odour emissions

Odour samples were collected in nalophan bags at the exhaust of the climate chamber using a vacuum sampling device manufactured by ECOMA (Honigsee, Germany). Samples were taken at the end of each experiment when the measured temperatures and gas concentrations were stable. Collected samples were analysed following procedures described in European guidelines (CEN, 2003). A standardised panel and an ECOMA (Honigsee, Germany) TO7 olfactometer were used for measurements of odour concentrations (OU_E). Odour emissions were calculated from measured odour concentrations and measured airflow rates. Odour analyses were carried out for samples 2 and 3 of the pig manure and for samples 1 and 2 of the cow manure.

2.2.3 Measuring the temperature

Thermocouples (Cu/CuNi) and a logger (INTAB Interface-Teknik AB, Stenkullen, Sweden) were used to measure and sample temperatures in the air inlet, the manure chamber, the air exhaust and the water bath. Temperatures at each experiment were calculated as the mean for about 5 minutes of measurements after the exhaust air concentrations had stabilised.

2.2.4 Measuring the manure chemical content

At the end of the measurements for each manure sample, a small quantity of the manure was collected and stored in a freezer. It was later sent to a laboratory (Eurofins) for chemical analyses. The DM content, total-N, NH_4^+-N, C/N ratio and pH, in the manure were measured. A sample of the wood shavings was also analysed for these parameters.

3. RESULTS

The manure composition, temperature and emissions ranges from the samples with and without wood shavings for the pig and cow manure are presented in Table 2 and Table 3, respectively. The ammonia emission from the pig manure (0.08–0.41 mg m^{-2} s^{-1}) was on average much higher than the ammonia emission from the cow manure (0–0.08 mg m^{-2} s^{-1}). The odour emission from the pig manure was high (21–930 OU m^{-2} s^{-1}) and significantly higher than the odour emission from the cow manure (1–6 OU m^{-2} s^{-1}).

Table 2. Manure characteristics, environmental parameters and emissions from the pig manure samples

	Sample 1		Sample 2		Sample 3	
Parameter	No WS	With WS	No WS	With WS	No WS	With WS
DM, %	18	21.3	20.7	26.1	16.8	25.7
Total-N, kg ton^{-1}	8.7	7.5	9.8	9.3	9	7.6
NH_4^+-N, kg ton^{-1}	3.9	3.2	3.9	3.4	4.9	3.4
C/N ratio	16	22	15	20	17	28
pH	7.6	8.2	7.5	8.1	7.6	8.2
Manure temperature, °C	16 – 27	15 – 30	15 – 25	16 – 25	15 – 26	17 – 26
Air temperature, °C	16 – 26	15 – 25	16 – 26	16 – 25	16 – 25	16 – 26
Water vapour, Pa	762 – 1083	788 – 1187	886 – 1049	882 – 1038	769 – 996	682 – 947
RH, %	26 – 45	27 – 50	27 – 53	32 – 51	26 – 46	27 – 46
NH_3, mg m^{-2} s^{-1}	0.13 – 0.22	0.1 – 0.39	0.08 – 0.21	0.09 – 0.36	0.18 – 0.20	0.18 – 0.41
CO_2, mg m^{-2} s^{-1}	0.22 – 0.73	0.28 – 1.59	0.75 – 1.51	1.60 – 2.29	0.30 – 0.55	0.92 – 1.80
Odour, OU m^{-2} s^{-1}	NA	NA	24 – 413	21 – 304	177 – 934	22 – 386

WS: wood shaving, NA: Not available (Odour was not analysed)

Table 3. Manure characteristics, environmental parameters and emissions from the cow manure samples

	Sample 1		Sample 2		Sample 3	
Parameter	No WS	WS	No WS	WS	No WS	WS

DM, %	12	17.7	12.3	16.9	10.2	18.7
Total-N, kg ton^{-1}	3.5	3.1	4	3.5	3.3	3.6
NH_4^+-N, kg ton^{-1}	0.6	0.5	1	0.7	0.9	0.7
C/N ratio	18	32	18	28	18	30
pH	7.5	7.7	8.2	8.2	7.6	8
Manure temperature, °C	16 – 23	16 – 24	14 – 24	16 – 26	15 – 26	17 – 28
Air temperature, °C	17 – 25	16 – 25	16 – 25	16 – 24	18 – 25	19 – 25
Water vapour, Pa	957 – 1147	905 – 1156	938 – 1284	889 – 1304	895 –1543	932 – 1535
RH, %	32 – 53	34 – 62	33 – 57	33 – 53	33 – 54	33 – 54
NH_3, mg m^{-2} s^{-1}	0.01 – 0.02	0 – 0.02	0.04 – 0.08	0.02 – 0.07	0.03 – 0.08	0.01 – 0.08
CO_2, mg m^{-2} s^{-1}	0.33 – 0.55	0.34 – 0.75	-0.10 – 0.56	0.68 – 1.15	0.44 – 0.79	0.89 – 0.41
Odour, OU m^{-2} s^{-1}	1.27 – 3.47	1.03 – 3.45	1.24 – 5.59	1.24 – 5.59	NA	NA

WS: wood shaving, NA: Not available (Odour was not analysed)

3.1 Influence of wood shavings on the manure composition

The wood shavings had the following composition: 88.5% DM, 1 kg ton^{-1} total-N (Kjeldahl method), 0.2 kg ton^{-1} NH_4^+-N (Kjeldahl method), 550 C/N ratio and a pH of 5.4. The addition of wood shavings led to increased DM, C/N ratio and pH levels for both the pig and cow manure samples (Table 4). It decreased the total-N and NH_4^+-N levels in both animal manure types (a slight discrepancy was observed for total-N in the third cow manure sample).

Table 4. Percentage change in the manure characteristics after adding wood shavings

Manure content	Pig manure			Cow manure		
	Sample1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
DM	18	26	53	48	37	83
C/N ratio	38	33	65	78	56	67
pH	8	8	8	3	0	5
Total-N	-14	-5	-16	-11	-13	9
NH_4^+-N	-18	-13	-31	-17	-30	-22

Values in this table were calculated from the measured values in Table 2 and Table 3

3.2 Relationships between emissions and environmental parameters

Correlation coefficients between ammonia and odour emissions and chosen environmental parameters are presented in Table 5. A positive correlation was found between the ammonia emissions and the manure temperature for both animal types. Odour emissions were positively correlated with the pig and with the cow manure temperatures for samples without wood shavings. Odour emissions and manure temperature were also positively correlated for the cow manure with wood shavings. Odour emissions were higher for the pig manure than for the cow manure with wood shavings, and for these samples a negative relationship was found between odour emissions and manure temperature. The air temperature and relative humidity did not significantly affect the ammonia or the odour emissions. Although the water vapour pressure was positively correlated with the emissions from the cow manure, this relationship could not be seen for the pig manure. Ammonia and odour relationships were positive for the pig and cow manure samples without wood shavings, and also for cow manure with wood shavings. This relationship was negative for the pig manure with wood shavings.

Table 5. Pearson's product-moment correlation coefficients between emissions and climate parameters

Pig manure	No wood shavings		Wood shavings	
	Ammonia	Odour	Ammonia	Odour
Manure temperature	0.70^{***}	0.40 (NS)	0.72^{***}	-0.70^{**}
Air temperature	0.18 (NS)	0.15 (NS)	0.11 (NS)	-0.16 (NS)
Relative humidity	-0.20 (NS)	-0.24 (NS)	-0.15 (NS)	0.06 (NS)
Water vapour pressure	0.06 (NS)	-0.23 (NS)	-0.06 (NS)	-0.23 (NS)
Ammonia/Odour correlation	0.40 (NS)		-0.51^{*}	
Cow manure				
Manure temperature	0.48*	0.75^{***}	0.69^{***}	0.47^{*}
Air temperature	0.20 (NS)	-0.09 (NS)	0.13 (NS)	0.05 (NS)
Relative humidity	0.24 (NS)	0.44 (NS)	0.36 (NS)	0.13 (NS)
Water vapour pressure	0.57^{**}	0.66^{**}	0.67^{***}	0.39 (NS)
Ammonia/Odour correlation	0.47^{*}		0.43 (NS)	

Level of significance *: $p \leq 0.05$, **: $p \leq 0.01$, ***: $p \leq 0.001$, NS: Not significant

Regression analyses were carried out for emissions and environmental parameters when significant correlations coefficients were observed. A Box-Cox transformation of the emissions was necessary in order to achieve normally distributed data with constant variances. The logarithm and square root were the optimal transformations. Linear regressions between the ammonia emissions and the pig manure temperature for the samples with and without the addition of wood shavings are shown in Figure 2. The coefficients of determinations were the same in both cases ($R^2 = 0.45$).

Regression analyses for the ammonia and odour emissions as a function of the cow manure temperature are shown in Figure 3. The strength of the relationships differed with manure composition which is reflected in the coefficients of determination in Figure 3.

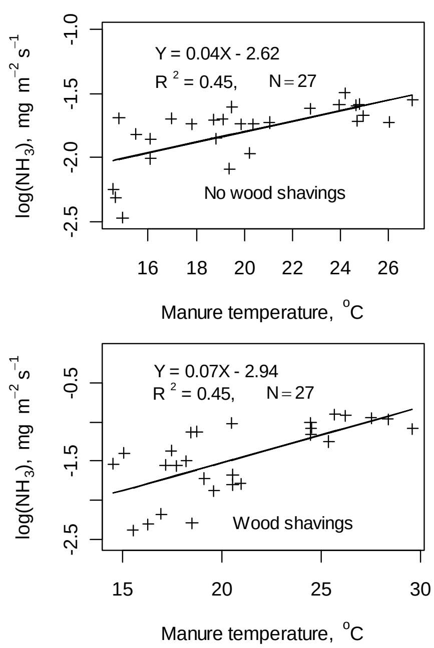

Figure 2. Regression of the ammonia emissions with the pig manure temperature

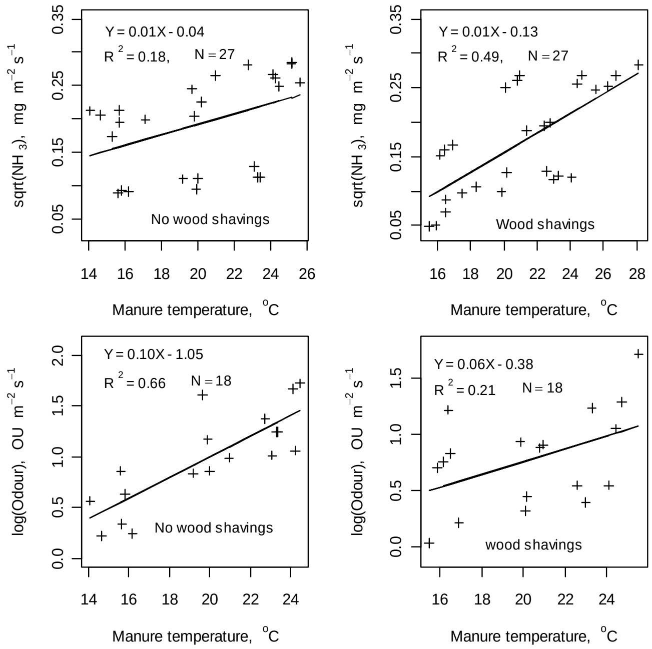

Figure 3. Regression of ammonia and odour emissions with the cow manure temperature

Regression analyses showed that the water vapour pressure had more influence on the odour than on the ammonia emissions from the cow manure without wood shavings (Figure 4). This could not be extended to the cow manure with wood shavings.

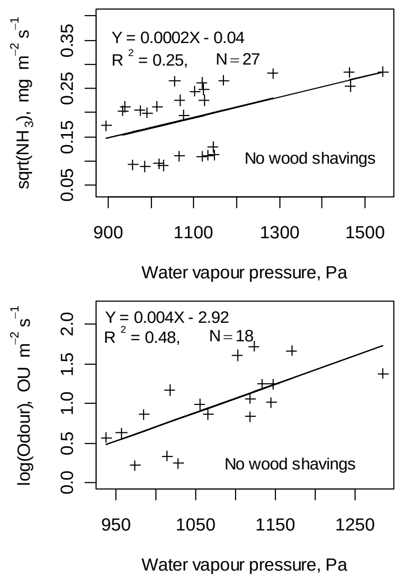

Figure 4. Ammonia and odour emissions as a function of the water vapour pressure for the cow manure without wood shavings

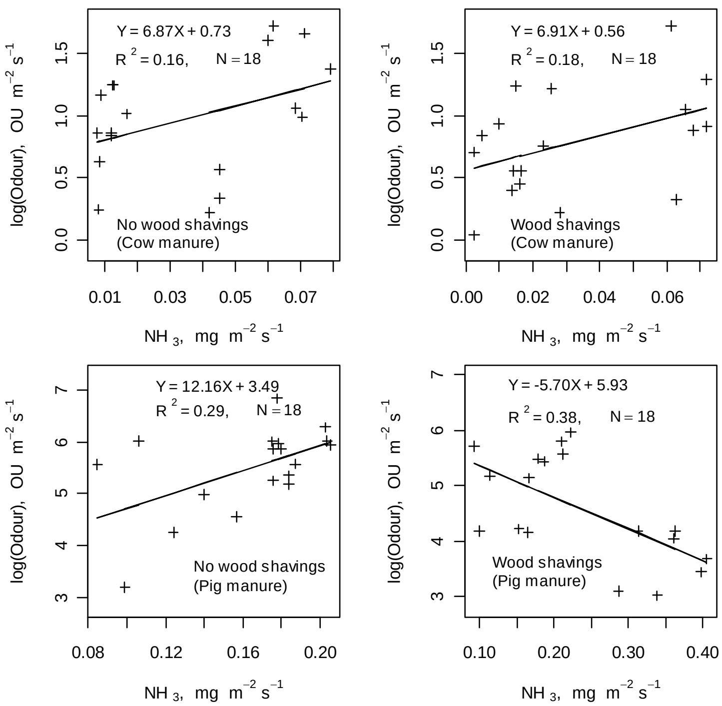

Figure 5. Relationship between odour and ammonia emissions from pig and cow manure

Variations in odour with ammonia emissions are presented in Figure 5. Odour release increased with ammonia up to an emission of about 0.25 mg m^{-2} s^{-1} for the pig manure with wood shavings. At higher ammonia emissions (0.28–0.40 mg m^{-2} s^{-1}), the odour emissions were lower.

3.3 Comparison of emissions from manure with and without wood shavings

The effects of adding wood shavings to the manure on the ammonia and odour emissions were analysed for each manure sample in a two-way ANOVA model shown in Eq. (2). When the differences were significant ($p < 0.05$), multiple comparison testing was carried out using Fisher's LSD test to determine which manure treatment had higher emissions.

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \lambda_k + \varepsilon_{ijk} \qquad (2)$$

where Y is the emission, μ is the overall mean emission, α is the treatment effect (with or without wood shavings), β is the effect of the manure temperature, λ is the time effect (days) of manure storage before analysis, ε is the error, i, j and k are levels in the factors.

The logarithm transformation was used when necessary to meet the criteria for ANOVA. β and λ were dropped from the model when they were not significant ($p \geq 0.05$). Figure 6 shows the difference in ammonia emissions when wood shavings were added to both animal manure types compared to the control.

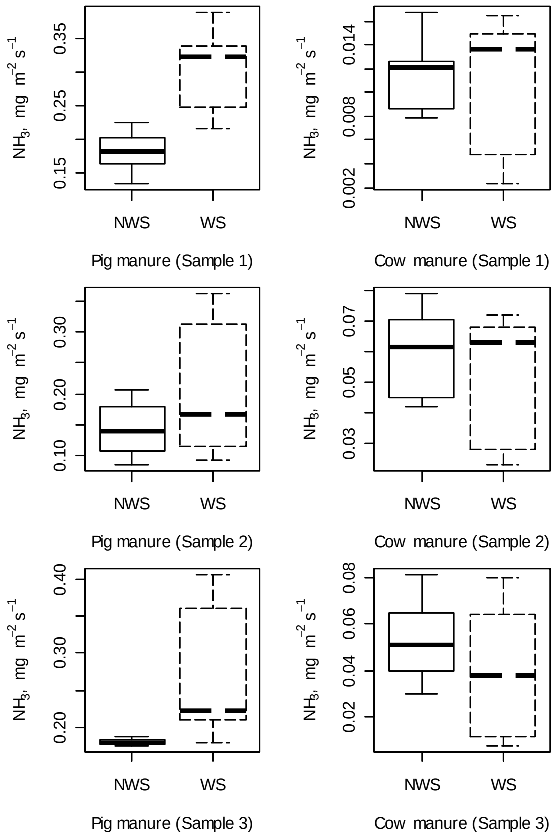

Figure 6. Comparison of ammonia emissions between manure with wood shavings (WS) and without wood shavings (NWS)

Ammonia emissions were higher ($p < 0.05$) from all the three pig manure samples with wood shavings compared to the control. They were lower ($p < 0.05$) from the cow manure with wood shavings in samples 2 and 3. There was no significant difference in the ammonia emissions from the cow manure in sample 1.

There was no significant difference in the odour emissions from the pig manure with and without wood shavings in sample 2, whereas in sample 3 the manure with wood shavings had a lower odour emission. There was also no significant difference in odour emissions from all the cow manure samples.

3.4 Methane and nitrous oxide emissions

No significant amounts of methane or nitrous oxide emissions were found in this study. However, small amounts of methane were observed during measurements of emissions from one sample in one treatment of the pig manure.

4. DISCUSSIONS

Ammonia emissions were higher from the pig manure when compared to the cow manure. Odour emissions were very much higher from the pig manure. A positive correlation was found between the ammonia emissions and the manure temperature for both the cow and pig manure. Odour emissions were positively correlated with the manure temperature for cow manure. Odour emissions also increased by manure temperature for the pig manure without wood shavings. The emissions from the cow manure were positively correlated to water vapour pressure but the relationship was not significant for the pig manure. The addition of wood shavings lowered the ammonia emissions from the cow manure but rather increased the emissions from the pig manure. Furthermore, no significant emissions of greenhouse gases were found in this study. One factor to consider when comparing emissions from the manure with and without added wood shavings is the size of the surface area. The manure without wood shavings had a rather smooth surface and thus a relatively small surface area, while the manure with wood shavings had a rough surface and thus a larger surface area.

The positive relationship between the manure temperature and the ammonia emissions for all the samples in the present study is supported by other publications (Van der Stelt et al. 2007; Andersson 1998). Lowering the temperature has been found to decrease ammonia emissions and in a study the ammonia emissions in a cow barn were reduced by 11–23% when incoming drinking water was passed through pipes in the manure gutter to cool the manure (Gustafsson et al. 2005). In the present study the ammonia emissions were about 2 times lower at manure temperatures of about 15 °C compared to emissions at about 25 °C, suggesting that lowering the manure temperature is an effective mitigation strategy.

The increase in odour emissions with increasing cow manure temperature has been supported in a laboratory experiment for pig manure (Le et al. 2005) and in a floor housing system for laying hens (Nimmermark and Gustafsson 2005). The non-significant or even negative relationship between the odour emissions and the pig manure temperature indicates that there are also other parameters of great importance for the formation and release of odour. Interestingly, it was observed that the pig manure samples with wood shavings had very low odour emissions at manure temperatures of 25 °C, but measured values at 20 °C were higher than values at 15 °C. Variations in microbial activity due to temperature and/or changes of the manure surface might be an explanation.

The air temperature did not significantly influence the ammonia and odour emissions, although positive correlations have been reported for barns, especially during low animal activity periods (Nimmermark and Gustafsson 2005; Jeppsson 2002; Le et al. 2005). A negative influence of ambient air temperature on ammonia emission was observed in a barn (Aarnink et al. 1993). Due to the experimental set up in the present study, it was likely that a different parameter like the manure temperature masked the effect of the air temperature. The manure temperature was not affected by air temperature, because the manure temperature was controlled by heating the water. It was also observed that when the manure temperature was high (~25 °C), it was difficult to set the air temperature to a lower value (~15 °C) due to heat transfer from the manure to the head space of the chamber. In addition, the duration of air temperature change might not have been long enough for convective heat transfer between the airflow boundary layer and the manure surface to be significant. In a barn, the air temperature should likely influence the manure temperature.

High pH values are considered to increase the emissions of ammonia and this was observed for the pig manure where samples with wood shavings had higher pH and higher ammonia emissions than those without wood shavings. The addition of wood shavings led to increased pH for the cow manure, but not to such an extent that it significantly increased the ammonia emissions. The pH of the wood shavings was 5.4 and could not have accounted for the higher pH levels of the manure after wood shavings were added. It has been shown that if the concentrations of the buffer components that control the slurry pH decrease due to volatilisation, the slurry surface pH will increase (Blanes-Vidal et al. 2009). The buffer components include the total inorganic carbon, total acetic acid and the total ammonium nitrogen (TAN). In particular, it was observed that the total-N decreased for the manure with wood shavings and this might contribute to the rise in the pH. Other research has confirmed the inverse relationship between manure pH and TAN (Le et al. 2005). Increase in pH during the initial stages of slurry storage has also been reported (Canh et al. 1998).

A recalibration of the multi-gas analyzer before measurements in each batch minimized the possibility of cross interference between water vapour and ammonia concentrations which might affect their correlations. The positive correlation between water vapour pressure and emissions from the cow manure in contrast to the pig manure might have been due to the higher water content of the cow manure as compared to the pig manure. The relationship between emissions and humidity in the presented study has been confirmed elsewhere. Positive correlations between odour emissions with water vapour pressure ($r = 0.92$) and ammonia emissions with water vapour pressure ($r = 0.78$) have been measured in a floor housing system for laying hens (Nimmermark and Gustafsson 2005), where r is the correlation coefficient. In a field study where fluxes were measured after the application of hog manure, it was found that ammonia volatilization increased with water vapour pressure deficit ($R^2 = 0.65$), where R^2 is the coefficient of determination (Mkhabela et al. 2009). A good correlation between ammonia emissions and vapour pressure deficit has also been reported ($R^2 = 0.53$) from dairy cattle manure (Gordon et al. 2001).

The addition of wood shavings to the cow manure increased the C/N ratio from 18 to 28–32 which is in the optimal range (25–35) for microorganisms to immobilise ammonium (Ekinci et al. 1998; Poincelot 1974). This explains the drop in ammonia emissions from the cow manure after wood shavings were added. In addition to the high C/N ratio of the wood shavings, the degradability of the carbon (C) is important as it is easily available to microbes and enhances ammonium immobilization (Tasistro et al. 2008; Sommer et al. 2006). The difference in the availability of C in wood shavings from different type of trees and in other bedding materials is due to the proportion of lignin; the higher the proportion of lignin (e.g. pine trees relative to wheat straw), the lower the degradability of the C (Martin et al. 1993; Tasistro et al. 2008). Resin and terpenes in the wood shavings may also reduce the degradation rate to some extent. At low C/N ratios, the excess nitrogen is emitted as ammonia while at high C/N ratios all the nitrogen is utilized for protein synthesis. Reductions in ammonia emissions have been reported after adding wood shavings to animal manure (Luo et al. 2004; Tasistro et al. 2008). The increase in ammonia emissions from the pig manure after wood shavings were added could be caused by a combination of different factors. The increase in C/N ratio after wood shavings were added was not within the optimal range except for one sample where it was 28. The increase in the pH after adding wood shavings contributed to increasing the ammonia emissions. It was also noted that the temperature of the pig manure with wood shavings increased faster than without wood shavings as compared to the cow manure. Lower heat capacity and self-heating due to microbial activity might explain this faster rise in temperature. This was also evident in higher CO_2 emissions for the manure samples with wood shavings relative to samples without wood shavings. These might explain the higher ammonia emissions from the pig manure with wood shavings in conformity with another previous research where it was also shown that manure with a higher DM eventually emits less ammonia over a longer period of time (Dewes 1999).

The anomaly seen in the ammonia and odour relationship has been reported elsewhere (Ogink and Koerkamp 2001). A non significant correlation between ammonia and odour concentrations has been measured (Fakhoury et al. 2000). However, it has been found that odour emissions are low for pig houses with low emissions of ammonia (Jongebreur et al. 2003). Interestingly, the ammonia and odour emissions from the cow manure were low, and for this type of manure as well as for the pig manure without wood shavings, the measurements indicated that a positive correlation might exist. A study suggests that ammonia contribution to odour concentration is only significant when hydrogen sulphide is absent (Blanes-Vidal and Hansen 2008). In other studies, a positive correlation between ammonia concentration and odour intensity has been measured (McGinn et al. 2003) and positive correlations in the emission rates have been reported (Wood et al. 2001). Positive relationships between ammonia and the concentrations of volatile organic compounds have also been utilised for emission rate calculations (Ngwabie et al. 2008).

Nitrous oxide and methane were not produced in measurable amounts from the manure. Low nitrous oxide emissions have been measured in cattle barns with slurry based manure handling (Ngwabie et al. 2009; Zhang et al. 2005). A move from straw to slurry based systems has been recommended in order to mitigate nitrous oxide emissions (Chadwick et al. 1999). The aerobic nature of the manure in the present study due to the continuous flow of air over the surface and the short storage duration might not be ideal conditions for methane formation. Given enough time, it is presumable that the generation of these gases might have reached measurable levels (Huther et al. 1997). Generally, these results show that irrespective of the type of manure, lowering its temperature is a potential method to reduce emissions. While the use of bedding material is good for the welfare of the animals, its emission reduction potential should be maximised by choosing appropriate materials (Jeppsson 1998, 1999). The proportions between manure and wood shavings in the study were (visually) comparable to what can be found at some commercial Swedish farms. However, proportions vary between different locations in a barn and between systems and management. Deep litter systems may have an uneven mixture of manure and bedding materials in different parts of the building due to the behaviour of the animals. The C/N ratio might therefore still be low in locations were the animals defecate and urinate. Mixing of the manure from time to time or frequent removal of the portions with high urine/faeces load might be useful.

5. CONCLUSIONS

The following conclusions can be drawn from the study of the effects of environmental factors and the addition of wood shavings on ammonia and odour emissions from fresh livestock manure:

- The ammonia emissions were positively correlated to the manure temperature. Emissions were about 2 times higher at manure temperatures of about 25 $^{\circ}$C when compared to emissions at about 15 $^{\circ}$C.

- The odour emissions were positively correlated to the cow manure temperature. Odour emissions had a positive tendency with the temperature of the pig manure without wood shavings. A positive correlation between the odour emissions and the temperature of the pig manure with wood shavings could not be found since odour emissions were low at temperatures of about 25 °C.
- The ammonia and odour emissions from the cow manure were positively correlated to the water vapour pressure although no influence of the relative humidity on the emissions was observed.
- The addition of wood shavings to animal manure does not seem to automatically mitigate ammonia or odour emissions as it also affects the temperature and the pH: it lowered the ammonia emissions from the cow manure but rather increased the emissions from the pig manure. Although the manure with wood shavings had a lower total-N and NH_4^+-N, the pH was higher than that of the manure without wood shavings. The temperature of the manure with wood shavings increased faster than that of the manure without wood shavings.
- There was an inconsistency in the relationship between the ammonia and odour emissions. However, a positive tendency seemed to be favoured. The measurements indicated a positive correlation for the cow manure as well as for the pig manure without wood shavings.
- Nitrous oxide and methane production from the fresh manure was not within the measurable levels of the multi-gas analyser.

Previous studies and the results in the present study indicate that climatic factors and the addition of bedding material significantly affect gaseous emissions from manure. There is the need for further studies to be carried out to understand how the addition of a material with a high DM content or C/N ratio affects emissions on a short as well as on a long term basis.

6. ACKNOWLEDGMENTS

We are grateful to our odour panel. This research was carried out with financial support from the Swedish Farmers' Foundation for Agricultural Research.

7. REFERENCES

Aarnink, A. J. A., M. J. M. Wagemans, and A. Keen. 1993. Factors affecting ammonia emission from housing for weaned piglets. In *European Association for Animal Production Publication; Nitrogen flow in pig production and environmental consequences*: PUDOC (Centre for Agricultural Publishing and Documentation) {a}.

Andersson, M. 1995. Ammonia volatilization from cow and pig manure - results from laboratory studies with a new climate chamber technique: *Swedish University of Agricultural Sciences*. Department of Biosystems and Technology, Lund, Sweden.

Andersson, M. 1998. Reducing ammonia emissions by cooling of manure in manure culverts. *Nutrient Cycling in Agroecosystem* 51 (1):73-79.

Blanes-Vidal, V., and M. N. Hansen. 2008. Emission of odorous compounds from pig slurry and their relationships with perceived odour concentrations. In *Agricultural and Biosystems Engineering for a sustainable world. International Conference on Agricultural Engineering*. Hersonissos, Crete, Greece: European Society of Agricultural Engineers (AgEng).

Blanes-Vidal, V., S. G. Sommer, and E. S. Nadimi. 2009. Modeling the Release of Gas and Odorous Compounds (H_2S, CH_3COOH, NH_3 and CO_2) from Swine Slurry. In *ASABE Annual International Meeting Sponsored by ASABE*. Grand Sierra Resort and Casino Reno, Nevada: ASABE.

Canh, T. T., A. J. A. Aarnink, M. W. A. Verstegen, and J. W. Schrama. 1998. Influence of dietary factors on the pH and ammonia emission of slurry from growing-finishing pigs. *Journal of Animal Science* 76 (4):1123-1130.

Chadwick, D. R., R. W. Sneath, V. R. Phillips, and B. F. Pain. 1999. A UK inventory of nitrous oxide emissions from farmed livestock. *Atmospheric Environment* 33 (20):3345-3354.

Dewes, T. 1999. Ammonia emissions during the initial phase of microbial degradation of solid and liquid cattle manure. *Bioresource Technology* 70 (3):245-248.

Ekinci, K., H. M. Keener, and D. L. Elwell. 1998. Composting short paper fiber with broiler litter and additives - alum, HiClay alumina and sulfuric acid: I. effects of initial pH and carbon/nitrogen ratio on ammonia emission. In *ASAE Annual International Meeting*. Orlando, Florida, USA.

Fakhoury, K. J., A. J. Heber, P. Shao, and J. Q. Ni. 2000. Correlation of odor detection thresholds with concentrations of hydrogen sulfide, ammonia and trace gases emitted from swine manure. In *ASAE Annual International Meeting*. Milwaukee, Wisconsin, USA: American Society of Agricultural Engineers.

FAO. 2006. Livestock's long shadow: Food and Agricultural Organisation.

Gordon, R., R. Jamieson, V. Rodd, G. Patterson, and T. Harz. 2001. Effects of surface manure application timing on ammonia volatilization. *Canadian Journal of Soil Science* 81 (3):525-533.

Groenestein, C. M., and H. G. Van Faassen. 1996. Volatilization of Ammonia, Nitrous Oxide and Nitric Oxide in Deep-litter Systems for Fattening Pigs. *Journal of Agricultural Engineering Research* 65 (4):269-274.

Groot Koerkamp, P W G. 1994. Review on Emissions of Ammonia from Housing Systems for Laying Hens in Relation to Sources, Processes, Building Design and Manure Handling. *Journal of Agricultural Engineering Research* 59 (2):73-87.

Gustafsson, G. 1996. Ventilation and air cleaning systems in agricultural buildings. Paper read at NIVA-course on occupational health, Proceeding, Norway, Nordic Institute for Advanced Training in Occupational Health, 6 - 10 May, at Helsinki.

Gustafsson, G., K. H. Jeppsson, J. Hultgren, and J. O. Sanno. 2005. Techniques to reduce the ammonia release from a cowshed with tied dairy cattle. *Agricultural Engineering International: the CIGR Ejournal* 7:Manuscript BC 04 010.

Hartung, J. 1992. Emission and control of gases and odorous substances from animal housing and manure stores. *Zentralblatt Fur Hygiene Und Umweltmedizin* 192 (5):389-418.

Hayes, E. T., A. B. G. Leek, T. P. Curran, V. A. Dodd, O. T. Carton, V. E. Beattie, and J. V. O'Doherty. 2004. The influence of diet crude protein level on odour and ammonia emissions from finishing pig houses. *Bioresource Technology* 91 (3):309-315.

Huther, L., F. Schuchardt, T. Willke, H. J. Ahlgrimm, and K. D. Vorlop. 1997. Methane and nitrous oxide emissions during storage and composting of cattle manure - a study using gas chromatography. In *Translation - Silsoe Research Institute*. Silsoe UK: Silsoe Research Institute.

Jeppsson, K. H. 1998. Ammonia emission from different deep-litter materials for growing-finishing pigs. *Swedish Journal of Agricultural Research* 28 (4):197-206.

Jeppsson, K. H. 1999. Volatilization of ammonia in deep-litter systems with different bedding materials for young cattle. *Journal of Agricultural Engineering Research* 73 (1):49-57.

Jeppsson, K. H. 2002. Diurnal variation in ammonia, carbon dioxide and water vapour emission from an uninsulated, deep litter building for growing/finishing pigs. *Biosystems Engineering* 81 (2):213-223.

Jongebreur, A. A., G. J. Monteny, and N. W. M. Ogink. 2003. Livestock Production and Emission of Volatile Gases. In *International Symposium on Gaseous and Odour Emissions from Animal Production Facilities*. 1-4 June 2003, 11-30, Scandic Hotel, Bygholm Park, Horsens, Denmark. CIGR, EurAgEng, NJF.

Jungbluth, T., E. Hartung, and G. Brose. 2001. Greenhouse gas emissions from animal houses and manure stores. *Nutrient Cycling in Agroecosystems* 60 (1-3):133-145.

Kai, P., P. Pedersen, J. E. Jensen, M. N. Hansen, and S. G. Sommer. 2008. A whole-farm assessment of the efficacy of slurry acidification in reducing ammonia emissions. *European Journal of Agronomy* 28 (2):148-154.

Le, P. D., A. J. A. Aarnink, N. W. M. Ogink, and M. W. A. Verstegen. 2005. Effects of environmental factors on odor emission from pig manure. *Transactions of the ASAE* 48 (2):757-765.

Luo, J., M. Kulasegarampillai, N. Bolan, and A. Donnison. 2004. Control of gaseous emissions of ammonia and hydrogen sulphide from cow manure by use of natural materials. *New Zealand Journal of Agricultural Research* 47 (4):545-556.

Luo, J., and S. Lindsey. 2006. The use of pine bark and natural zeolite as biofilter media to remove animal rendering process odours. *Bioresource Technology* 97 (13):1461-1469.

Martin, A. M., J. Evans, D. Porter, and T. R. Patel. 1993. Comparative Effects of Peat and Sawdust Employed as Bulking Agents in Composting. *Bioresource Technology* 44 (1):65-69.

McGinn, S. M., H. H. Janzen, and T. Coates. 2003. Atmospheric ammonia, volatile fatty acids, and other odorants near beef feedlots. *Journal of Environmental Quality* 32 (4):1173-1182.

Mkhabela, M. S., R. Gordon, D. Burton, E. Smith, and A. Madani. 2009. The impact of management practices and meteorological conditions on ammonia and nitrous oxide emissions following application of hog slurry to forage grass in Nova Scotia. *Agriculture, Ecosystems & Environment* 130 (1-2):41-49.

Monteny, G. J., and J. W. Erisman. 1998. Ammonia emission from dairy cow buildings: A review of measurement techniques, influencing factors and possibilities for reduction. *Netherlands Journal of Agricultural Science* 46 (3-4):225-247.

Ngwabie, N. M., K.-H. Jeppsson, S. Nimmermark, C. Svensson, and G. Gustaffson. 2009. Multi-location measurements of greenhouse gases and emission rates of methane and ammonia from a naturally ventilated barn for dairy cows. *Biosystems Engineering.* 103 (1):68-77.

Ngwabie, N. M., G. W. Schade, T. G. Custer, S. Linke, and T. Hinz. 2008. Abundances and Flux Estimates of Volatile Organic Compounds from a Dairy Cowshed in Germany. *Journal of Environmantal Quality* 37 (2):565-573.

Nimmermark, S, and G. Gustafsson. 2005. Influence of temperature, humidity and ventilation rate on the release of odour and ammonia in a floor housing system for laying hens. *Agricultural Engineering International: the CIGR Ejournal* 7:Manuscript BC 04 008.

Nimmermark, S. 2004. Odour influence on well-being and health with specific focus on animal production emissions. *Annals of Agricultural and Environmental Medicine* 11 (2):163-173.

Ogink, N. W. M., and Pwgg Koerkamp. 2001. Comparison of odour emissions from animal housing systems with low ammonia emission. *Water Science and Technology* 44 (9):245-252.

Philippe, F. A., M. Laitat, B. Canart, M. Vandenheede, and B. Nicks. 2007. Comparison of ammonia and greenhouse gas emissions during the fattening of pigs, kept either on fully slatted floor or on deep litter. *Livestock Science* 111 (1-2):144-152.

Poincelot, R. P. 1974. A scientific examination of the principles and practice of composting. *Compost Science* 15 (3):24-31.

Schiffman, S. S., J. L. Bennett, and J. H. Raymer. 2001. Quantification of odors and odorants from swine operations in North Carolina. *Agricultural and Forest Meteorology* 108 (3):213-240.

Sommer, S. G., G. Q. Zhang, A. Bannink, D. Chadwick, T. Misselbrook, R. Harrison, N. J. Hutchings, H. Menzi, G. J. Monteny, J. Q. Ni, O. Oenema, J. Webb, and L. Sparks Donald. 2006. Algorithms Determining Ammonia Emission from Buildings Housing Cattle and Pigs and from Manure Stores. In *Advances in Agronomy*: Academic Press.

Statistics-Sweden. 2007. Statistick årsbok för Sverige 2007, [Statistics yearbook of Sweden 2007]. Emissions of ammonia to air in Sweden in 2007. (English summary): http://www.scb.se.

Tasistro, A. S., M. L. Cabrera, C. W. Ritz, and D. E. Kissel. 2008. Manipulating bedding materials and PLT (TM) to reduce NH_3 emissions from broiler manure. *Bioresource Technology* 99 (6):1952-1960.

Van der Stelt, B, E. J. M. Temminghoff, P. C. J. Van Vliet, and W. H. Van Riemsdijk. 2007. Volatilization of ammonia from manure as affected by manure additives, temperature and mixing. *Bioresource Technology* 98 (18):3449-3455.

Verdoes, N., and J. J. Zonderland. 1999. The effect of a chemical air scrubber on ammonia emission from a growing-finishing pig house. In *Proefverslag - Praktijkonderzoek Varkenshouderij*. Rosmalen Netherlands: Proefstation voor de Varkenshouderij.

Wood, S. L., D. R. Schmidt, K. A. Janni, L. D. Jacobson, C. J. Clanton, and S. Weisberg. 2001. Odor and Air Emissions from Animal Production Systems. Paper read at ASAE Annual International Meeting Sponsored by ASAE, July 30-August 1, 2001, at Sacramento Convention Center, Sacramento, California, USA.

Yamulki, Sirwan. 2006. Effect of straw addition on nitrous oxide and methane emissions from stored farmyard manures. *Agriculture, Ecosystems & Environment* 112 (2-3):140-145.

Zhang, G., J. S. Strom, B. Li, H. B. Rom, S. Morsing, P. Dahl, and C. Wang. 2005. Emission of Ammonia and Other Contaminant Gases from Naturally Ventilated Dairy Cattle Buildings. *Biosystems Engineering* 92 (3):355-364.