AMMONIA AND ODOUR ABATEMENT METHODS FOR THE NI PIG INDUSTRY

DARD E&I Project 13/04/03

Magowan, E., Kennedy, T., Mansoor, F., Farmer, L. J.

April 2015

CONTENTS

	Page
Summary	**3**
Chapter 1 Introduction	**4**
Chapter 2 Creation of Ammonia and Odour	**7**
Chapter 3 Ammonia and Odour Abatement techniques and their effectiveness	**22**
Chapter 3A Abatement from the pig	**23**
Chapter 3B Housing design above slats	**42**
Chapter 3C Housing design below slats	**54**
Chapter 4 Conclusion	**59**
Further Research	**61**
References	**63**
Appendix	**81**

Summary

- This paper reviews published reviews and research on the cause and abatement of ammonia and odour emissions from pig-houses and manure.
- Ammonia is formed when urine and faeces meet and the most economically abatement method (within limits) for ammonia emissions is by dietary means. Other key abatement methods involve the fundamental separation of faeces from urine but such methods can incur significant cost.
- The most important compounds contributing to the odour from pig-houses were identified as sulphur compounds, especially hydrogen sulphide, p-cresol and other phenols, skatole and indole, ammonia and low molecular weight organic acids.
- Many of these compounds arise from the microbial activity of the gastrointestinal tract or microbial breakdown of the faeces.
- Differences between the methods of odour measurement make comparison of data between studies difficult, and may mean that many studies under or over estimate the concentrations of some compounds.
- The release of odour from pig-houses is influenced by diet, dust, climatic conditions as well as housing design below and above the slats.
- Some methods have been tested for odour abatement but it is noted that more research is required in this area. However, air scrubbers appear to be commonly used but can be extremely expensive to both install and maintain.
- Most studies address the odour compounds important for odour inside or close to pig houses and the evaluation of the compounds important downwind from pig-houses was hampered by a lack of quantitative data.

Chapter 1 Introduction

Pork is currently the most widely consumed meat product in the world, accounting for 38% of total meat consumption. By 2050, worldwide pig consumption is expected to increase by 40% owing to demographic growth, changes in food preferences and agricultural intensification (FAO, 2011). The impact of livestock production on the environment is attracting increasing attention, especially the effects on pollutant gases like ammonia and greenhouse gas emissions (carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)). Globally, livestock production accounts for 64% of ammonia emissions and 18% of anthropogenic emissions of cumulated greenhouse gases (FAO, 2006). In Europe, pig production represents nearly 25% of the livestock emissions (European Environment Agency, 2010).

Ammonia (NH_3) can be emitted from animal houses, solid or liquid manure stores, compost heaps and manure applied to fields (Sommer et al. 2003, 2006). Ammonia is a reactive gas that combines readily with NO_3^- and SO_4^{2-} to form particulates, which are a risk to human health (Renard et al. 2004). In addition, deposited NH_3 and wet and dry-deposited particulate ammonium may cause acidification and eutrophication of natural ecosystems (Brandt et al. 2011; Sutton et al. 2011). Ammonia also contributes to anthropogenic greenhouse gas emissions, being a significant source of indirect N_2O emissions that result from land deposition and is thus included in the GHG emission inventories (IPCC 2006).

In the UK ammonia emissions are dominated by those from cattle production (Table 1) and within livestock production the largest sources of NH_3 emissions are buildings in which livestock are housed, followed closely by land spreading. With regard to pig production Philippe et al. (2011) noted that buildings were responsible for about 50% of pig NH_3 emissions.

Odour nuisance is an old but dominating problem of air pollution on a local level. Increasing numbers of people complain about odour in the neighbourhood of livestock farms. One reason is that the structure of populations in villages is changing and village populations are growing due to new housing developments. On the other hand livestock production has become highly intensive and as a result more animals are housed per unit of area. Currently the prognosis and assessment of odour emissions in the vicinity of livestock farms can decide on their continuation and capacity of development

Table 1. UK ammonia emissions in 2011 by major source

Livestock production sector	kt NH_3
Dairy	71.3
Beef	57.6
Poultry	30.8
Pigs	17.6
Sheep	9.5
Other major source	
N Fertilizer	39.7

Since ammonia, along with other gases, and odour present challenges to the environment several key pieces of legislation exist to manage their emission. These include the Nitrates Directive and Water Framework directive which, with regard to livestock production, are largely concerned with Nitrogen and Phosphorus emissions. The directives concerning the control of ammonia and odour include the 'Environment Impact Assessment' (EIA) and 'Integrated Pollution Prevention Control' (IPPC). Recently IPPC has been replaced by 'The Environmental Permitting Regulations' (EPR) but the ethos of the directive is largely the same. The EIA ensures that all projects including animal husbandry which are likely to have significant (negative) effects on the environment are subject to an environmental impact assessment in the planning stages. IPPC is then designed to avoid, reduce and control the release of substances to air, land, water and therefore reduce the overall impact on the environment and human health by any activity, especially industrial and agricultural activities.

Lastly the Gothenburg protocol sets targets for the reduction of some key polluting gases. The Gothenburg protocol requires EU member states to cut their emissions of sulphur dioxide by 59%, nitrogen oxides by 42%, ammonia by 6%, volatile organic compounds by 28% and particles by 22% between 2005 and 2020.

The following review aims to provide information to DARD and stakeholders with regard to the creation, contributing factors and abatement strategies for ammonia and odour so that the aforementioned pieces of legislation and government targets can be met. The review will focus on 'buildings' since it is well accepted that 'trailing shoe' techniques for land spreading and covering of slurry stores can significantly reduce emissions external to the 'pig building'. However the creation and control of odour and ammonia within 'pig buildings' is multi factorial.

Chapter 2 Creation of Ammonia and Odour

Ammonia

Nitrogen is excreted from pigs via faeces or urine. Nitrogen in faeces is mainly present in the form of protein while nitrogen in urine is mainly present in the form of urea. The main source of NH_3 is the rapid hydrolysis of urea by the enzyme urease. Depending on the acidity of the slurry Urea is converted to either ammonium or ammonia. This reaction happens rapidly when urea comes in contact with urease.

Urease is produced by a wide variety of microbial organisms which are present in faeces but not urine. Therefore, urine must mix with faeces for the conversion to occur. Urease is a cytoplasmic enzyme largely present in faecal bacteria (Mobley and Hausinger, 1989). In livestock buildings, it is present in abundance on fouled surfaces like floors, pits and walls (Ni et al., 1999). Urease activity is affected by temperature with low activity below 5–10°C and above 60°C (Sommer et al., 2006). Under practical conditions, models show an exponential increase of urease activity related to temperature (Braam et al., 1997). Urease activity is also affected by pH with optimum conditions ranging from 6 to 9, while animal manure pH is usually buffered to between 7.0 and 8.4. Therefore, optimal conditions for complete urea hydrolysis are largely met in animal husbandry, making the urea availability the limiting factor. The NH_4^+ production depends also on manure moisture content because water is necessary for bacterial activity (Groot Koerkamp, 1994). Thus, NH_4^+ production is optimal between 40% and 60% moisture content but release decreases at values above and below this range. Ammonia production stops below 5–10% moisture content (Elliot and Collins, 1983).

Nitrogen in faeces is present as a result of undigested protein and the degradation of this protein can also be a source of ammonia but the process is much slower (months to years) (Zeeman, 1991). Ammonium (which is water soluble and therefore not readily volatilised), is created when the pH of the slurry is acidic (pH < 7) or neutral (pH 7). Ammonia, which is readily volatilised, is created when conditions are alkaline (pH > 7). Le et al (2005) found that in a solution pH of 9.24, ammonium (NH_4^+) and ammonia (NH_3) (aq) are present in equal proportions. Below

Ph 7, ammonium (NH_4^+) is predominant and therefore volatilisation of ammonia is reduced.

Release of ammonia

Ammonia release from liquid manure inside swine houses is associated with the NH_3 concentration difference between the manure and the air above the manure, manure pH, manure temperature and the air temperature and air velocity over the manure surface (Ni. *et al*., 2000). Zhang *et al*. (1994) adds that the nitrogen content of the manure is also a major factor. The NH_3 concentration difference between the liquid manure phase and the air phase is the driving force of mass transfer of NH_3 release. The pH and temperature affect the free ammonia concentration in the liquid manure. The temperature and air velocity govern the convective mass transfer process. The air velocity over the manure surface in a swine house is directly related to the ventilation of the house (Ni. *et al*., 2000). In recent work by Berthiaume *et al*. (2007) a sensitivity analysis of a deterministic model for the prediction of daily nitrogen concentration in slurry and inside buildings and storage facilities was performed. In their work they noted that the most important factors which affected the output of values included the proportion of protein in the feed, the temperature of the slurry, the pH of the slurry and the air speed over the slurry. The surface area of the slurry is also deemed important.

Chemical compounds associated with odour from piggery units

Over recent years the number of scientific publications dealing with all issues surrounding the emission of obnoxious odours from agricultural activities such as pig rearing has steadily increased. One major literature review, carried out by O'Neill and Phillips (1992) revealed 168 chemical compounds which had been identified in livestock waste or in the air around it. However with the current availability and range of more sophisticated sample and analysis techniques, researchers have reported hundreds of different chemicals being emitted from pig production facilities. Schiffman (2001), Hamon (2012) and Ni (2012) reported the identification of approximately 331, 400 and 500 volatile organic compounds (VOCs) respectively, in their reviews of research into swine facilities. The main VOCs identified in pig livestock waste is reported in the Appendix. The list includes not only the prominent noxious odour compounds but also many odorous chemicals which may make only a small contribution to the "bad odour" problem due to their low concentration and/or high odour detection threshold.

Although a great number of odorous compounds have been identified from animal production facilities, the information on them often provides an insufficient distinction between the various sources from which they originate. As a consequence of natural chemical or biochemical processes, chemical odours from livestock buildings may change in both concentration and offensiveness dependant on the different source areas within pig rearing facilities. The odour from the waste itself may differ from its immediate vicinity and the building air overall, to the ventilated air from the building and the air downwind from the piggery building. There are, therefore, quite large variations in the concentrations of these odorous compounds reported in the literature (Ni *et al*., 2012; O'Neill and Phillips, 1992; Schiffman *et al*., 2001; Hamon *et al*., 2012; Le *et al*., 2005) due to not only the sampling source but also from changes that have taken place in the last 30 years in pig production systems (e.g. diet, and animal housing design). Other factors affecting the wide variation of concentration data for chemicals are both the particular sample collection and measuring methods used by the various researchers and these will be discussed below (Ni *et al*., 2009; Trabue *et al*., 2008).

The main compound classes associate with odour from pig facilities can be grouped as follows (Le et al., 2005):

1. <u>Volatile fatty acids (VFAs)</u>: The most dominant acids in this class are acetic, propanoic, butanoic (butyric), 2-methylpropanoic (isobutyric), 3-methylbutanoic (isovaleric), pentanoic (valeric), hexanoic and capric acids. The odorous nature of VFAs progresses from the pungent smell of acetic acid to the distinctly unpleasant and offensive smell of pentanoic and capric acids. Those VFAs with an unpleasant and offensive smell each have a lower detection threshold than the pungent smell of acetic acid. They are produced from proteins and carbohydrates under anaerobic conditions in the large intestines of animals and

also in manure storage where they can be volatilised to cause malodour (Le *et al*., 2005).

2. Sulphurous compounds: The most commonly reported sulphurous compounds identified in air from piggery facilities include hydrogen sulphide, methyl mercaptan (methanethiol), dimethylsulphide, dimethyldisulphide, dimethyltrisulphide and carbon disulphide. Sulphurous compounds are the most offensive odour compounds and their odorous nature progresses from the putrid smell of dimethysulphide and methyl mercaptan to the rotten eggs of hydrogen sulphide. In general, sulphurous compounds have higher concentrations than VFAs and also lower detection thresholds and as a result may cause more odour nuisance than VFAs. Sulphur-containing compounds are produced by anaerobic bacteria from two main sources: sulphate reduction in urine and metabolism in manure of sulphur-containing proteins or amino acids (cysteine and methionine). The sulphurous compounds formed volatilise to create the malodour (Le *et al*., 2005).
3. Phenols and indoles: The major phenolic compounds are phenol, 4-methylphenol (para-cresol) and 4-ethylphenol and the main indolic compounds are indole and 3-methylindole (skatole). These two classes of compounds are considered as the main compounds responsible for the smell in pig-house ventilation air O'Neill and Phillips (1992). The concentration of p-cresol found in piggery air is higher than other phenols and indoles and this, together with a low detection threshold, makes it an important compound for odour nuisance. Other important compounds are indole and skatole. Phenolic compounds, such as p-cresol and 4-ethylphenol, are produced from microbial fermentation of tyrosine and phenylalanine in the intestinal tract of animals and in manure storage. Metabolism of tryptophan results in the production of indole which is subsequently converted into skatole Mackie (1994).
4. Ammonia and volatile amines: During manure storage, ammonia is the main nitrogenous compound produced, whilst, in comparison, volatile amines, such as trimethylamine, are produced in low concentrations. Ammonia, which has a sharp and pungent smell, is mainly sourced from the breakdown of urea found in urine and manure Spoelstra (1980). Volatilisation of ammonia from manure into the air can be a slow process and is dependent on factors such as

concentration, pH and temperature as previously mentioned. A lesser release of ammonia is from deamination of proteins and amino acids when used as energy sources by bacteria. Volatile amines are produced by microbial metabolism, under anaerobic conditions, of protein-containing products (Spoelstra (1980).

For this review, a table containing 28 of the key problem odour chemicals most often cited in the literature as being found in and emitted from pig house facilities, is presented in Table 2. The table includes, for each chemical compound, a reported concentration range as determined by a laboratory analytical technique, a description of the odour and the odour detection threshold range value. The odour detection threshold for a chemical compound is a way of identifying compounds of greatest nuisance and can be defined as the lowest concentration of a single compound in air that can be detected by the human olfactory sense when compared to a non-odorous sample (Parker *et al*., 2012). Odour detection thresholds reported for single chemical compounds are highly variable resulting in a wide range of reported values for most odorant compounds (Blanes-Vidal *et al*., 2009a). The odour detection limits used in Table 2 reflect the range of values quoted in the scientific literature based on the average of when the odour becomes detectable to 50% of a panel of trained olfactometric assessors.

In order to enable comparisons to be made, this review used the odour activity value (OAV) for assessing the relative importance of an individual compound in a complex odour mixture. The OAV is defined as the concentration of a single compound divided by the odour threshold value for that compound (Trabue *et al*., 2006) and OAVs for each chemical compound are listed in Table 2. Compounds with an OAV greater than 1.0 would likely contribute to the overall odour of a sample mix and compounds with large OAV would contribute substantially. This method is commonly used in flavour chemistry but rarely in studies of pig-house odour. A comparison was made, as shown in Table 2, between the ranking of OAVs found from this review with OAV values calculated from experimental data presented by Parker et al. (2012) on the measurement of odorous chemicals emitted from animal buildings. The comparison showed relatively good agreement with hydrogen sulphide and p-cresol ranked 1st and 2nd respectively in each assessment and, out of the nine ranked compounds listed by Parker, six of them appeared in the top nine of the review reported here. This would tend to indicate that there are a relatively small number of identifiable problem odour compounds which have a predictable pattern of persistence and occurrence in pig house facilities and identification of those compounds is crucial for developing strategies to control them. The data collected from this exercise went forward for meta analysis, the results of which are reported in a separate document by Kennedy *et al* (2014). In summary the meta analysis concluded that the most offensive odours from pig houses were :

Short-chain acids. C4 and C5 straight chain and branched chain acids, especially butanoic acid, pentanoic acid and 3-methylbutanoic acid. These compounds have unpleasant odours of faeces or rancid cheese.

Sulphur compounds. These compounds can be difficult to measure, but when recorded are at levels likely to contribute to odour. Hydrogen sulphide is especially odorous but methylmercaptan and related sulphides and disulphides are also involved. H_2S smells of rotten eggs while the other sulphur compounds smell of rotten vegetables.

Phenols. 4-Methylphenol makes a major impact but phenol and 4-ethylphenol are likely also to contribute. The compound, 4-methylphenol, has a faecal odour whilst the other two have a pungent aromatic smell.

Indoles. 3-methylindole and indole are highly odorous compounds with odours of faeces. 3-methylindole, also known as skatole, is responsible for the characteristic odour of pig slurry.

Amines. Trimethylamine and ammonia contribute to the odour in pig houses but in most cases are not the major odour compounds.

The above compounds are listed in approximate order of importance for pig-house odour, though their relative importance can vary.

Recent work by Trabue et al. (2011) included the combined use of gas chromatography with olfactometry for the chemical analysis of pig odours. Analyses were made both on pig house air and headspace odour emitted from pig manure over a period of weeks and the chemical odorant concentrations converted to OAVs. Based on the OAV data, the chemical compounds with key odour impact found in pig house air were p-cresol and skatole, and VFAs isovaleric, butyric and valeric acids. For manure headspace odours, the OAV values showing greatest impact were hydrogen sulphide, p-cresol and skatole and ammonia. The OAV values for hydrogen sulphide, skatole and ammonia increased strongly with aging of the manure.

Other factors affecting pig house odour are listed below

Dust

As with odour pollutants emanating in and from piggery buildings, dust pollution represents the solid part of aerial emissions. Odour emissions from confined animal housing are enhanced due to the role of respirable dust, sometimes termed as particulate matter (PM) to describe airborne particles, concentrating and transporting those odours (Hartung 1985). The major component of dust or PM from piggeries is organic (Aarnick *et al*., 1999)**.** The review by Hamon et al. (2012) lists the major components of piggery dust as being comprised of animal hair, skin, dried faeces, urine, dander, microbial and bacterial matter and bedding particles. It also includes components from feed materials and from mould, pollen grain mites and insect parts. The review also noted from the literature that all odour compounds may prefer to be fixed on to dust rather than existing in the gaseous phase: 2% of the dust mass is attributed to odorants. The review of the literature by Hamon et al (2012) mainly reports that dust concentrates are lower in housing with a fully slated floor than in those with a non-slatted floor. A review by Cambra-Lopez et al 2010) on airborne PM from livestock facilities noted that most of the chemicals responsible for bad odour in piggeries have been identified as being bound to PM and that the relative abundances of such compounds are higher in smaller particulates. Bottcher (2001) reported that odours attached to airborne particulate may increase the persistence of the odour as it disperses away from the source. Through the literature review by Hamon et al (2012), they demonstrated that the problems of odour are intrinsically linked to the problems of dust removal because VOCs can be fixed on to the dust and some treatment methods are common to both pollutants.

Climate and Meteorological conditions

Weather is one of the most important factors that dictate odour dispersion. The climatic effects of particular weather conditions such as wind velocity, direction, temperature, cloud cover and atmospheric stability will all significantly affect odour plume dispersion and plume rise from the pig production unit and hence influence perception of an odour (Sheridan *et al*., 2004). Research work by Xing et al (2007) looked at the effects of dispersion models to climatic parameters for pig odour dispersion. They found that under steady–state weather conditions, the results indicated that the odour dispersion was mainly affected by atmospheric stability, wind speed, wind direction and air temperature. Odour transport was favoured by stable atmospheric conditions, low wind speed and high ambient temperature.

Table 2. Key Volatile organic compounds (VOCs) identified in pig production facilities.

COMPOUND	Air concentration[a] (mg m^{-3})	Odour detection threshold[b] (mg m^{-3})	Odour Activity Value[f] (OAV)	Odour descriptive	OAV ranking from this literature review	OAV ranking from separate study[g]
Acids						
Acetic acid	0.075-0.11	0.025[e]-0.363[c]	0.2 - 4.4	Irritant, pungent		
Propanoic acid	0.040-0.062	0.003[e]-0.110[c]	0.4 - 20.6	Irritant, pungent, faecal	12	8
Butanoic acid (Butyric acid)	0.0386-0.220	0.0004[e]-0.0145[c]	2.66 - 550	Irritant, rancid, stench	5	3
2-Methylpropanoic acid (Isobutyric acid)	0.0084-0.015	0.005[e]-0.0724[c]	1.16 - 3	Irritant, pungent		
Pentanoic acid (Valeric acid)	0.0015-0.006	0.0008[e]-0.0204[c]	0.74 - 7.5	Irritant, unpleasant, faecal	18	4
3-Methylbutanoic acid (Isovaleric acid)	0.0141-0.064	0.0002[e]-0.0105[c]	1.34 - 320	Rancid, cheese, faecal	8	6
2-Methylbutanoic acid	0.013	0.00794[c]-0.02[e]	0.2 - 0.7	Irritant, stench		
Hexanoic acid	0.0015-1.095	0.02[e]-0.0603[c]	0.075 - 18.1	Irritant, sour cheese	14	
4-Methylpentanoic acid	0.005-0.026	0.037[e]-0.0759	0.131 - 0.703	Irritant, pungent, cheese		
Heptanoic acid	0.005-0.051	0.022[e]-0.148[c]	0.23 - 2.32	Irritant, disagreeable, rancid		
Aldehydes						
Acetaldehyde	0.00734	0.0027[e]-0.339[c]	0.02 - 2.7	Pungent		
Nonanal	0.0052	0.0003[e]-0.0135[c]	0.38 - 17.2	Irritant	15	
Amines						
Trimethylamine	0.00049-0.005	0.00026[e]-0.00589[c]	0.08-19.0	Irritant, fishy, pungent	13	
Ammonia	0-18	0.03[e]-4.07[c]	0 - 600	Sharp, pungent	4	9
Ketones						
Acetophenone	0.0005-0.019	0.01[e]-1.82[c]	0.05 - 1.9	Irritant		
Nitrogen compounds						
Indole	0.00049-0.005	0.0006[e]	0.8 - 8.3	Irritant, intense faecal odour,	16	
3-Methylindole (skatole)	0.0017-0.044	0.00035[e]-0.00309[c]	0.55 - 125.7	Stench, intense faecal odour,	9	7
Phenols						
Phenol	0.0078-0.033	0.022[e]-0.427[c]	0.355 - 1.5	Irritant		
4-Methylphenol (p-cresol)	0.041-0.26	0.00005[e]-0.00832[c]	4.93 - 5200	Irritant, faecal	2	2
2-Methoxyphenol	0.00052	0.0037[e]-0.00525[c]	0.1	Irritant		
4-Ethylphenol	0.002-0.395	0.0.0035[e]-0.01[c]	0.57 - 112.8	Irritant, pungent	10	
Sulphur compounds						
Hydrogen sulphide	0.004-2.4	0.0001[e]-0.0257[c]	0.15 - 24000	Rotten eggs	1	1
Dimethylsulphide	0.0005-1.528	0.0003[e]-0.00589[c]	0.09 - 509.3	Stench, putrid, disagreeable	6	
Dimethyldisulphide	0.002-1.14	0.0011[e]-0.0479[c]	0.041 - 1036	Stench, putrid, disagreeable	3	
Diethylsulphide	0.0035-0.011	0.0014[e]-0.0145c	0.24 - 7.86	Stench, putrid	17	5
Dimethyltrisulphide	0.002-0.574	0.0073[e]-0.00871[c]	0.229 - 78.6	Stench, putrid	11	
Diphenylsulphide	0.0045	0.0026[e]-0.00776[c]	0.580 - 1.730	Stench, putrid		
Methyl mercaptan (methanethiol)	0.108-0.813	0.00209[c]	51.7-389.0	Unpleasant	7	

[a]Sources for findings of compounds in the atmosphere at pig rearing facilities include **Hamon et al (2012) (*4*)**; **O'Neill and Phillips (1992) (*2*)**; **Ni et al (2012) (*1*)**; **Parker, et al (2012) (*14*)**; **Chmielowiec-Korzeniowska (2009) (*15*)** ; **Blanes-Vidal et al (2009) (*11*)**. Compounds marked with ✓ refer to those identified but not quantified as reported by **Schiffman et al (2001) (*3*)** . [b]Odour detection thresholds are given in milligrams per cubic metre and

reported values are from [c]**Devos et al (1990) (*16*)** , [d]**Ruth (1986) (*17*)** and [e]**Van Gemert et al (1977) (*18*)**. Odour Activity Value (OAV) is defined as the concentration of a single chemical compound divided by the odour threshold for that compound. Those compounds with an OAV ≥ 1 are likely to contribute to the overall odour of an air sample, OAV study by [g]**Parker et al (2012) (*10*)**.

Considerations when measuring odour

Impact of sample location for odour collection.

Sampling sources for odour collection can vary widely within the reported scientific literature leading to a large variation in the reported levels of VOCs. A comprehensive review by Ni et al. (2012) summarises the large body of scientific work reported by research groups on the measurement of odour compounds emitted by confined pig production facilities, with the following air sample sourcing sites being the main focuses of their research:

1. Air in confined spaces, such as inside the housing and in headspaces of manure storages and dead animal compost.
2. Air in the open atmosphere above pig slurry/wastewater surfaces.
3. Ambient air surrounding pig production facilities.
4. Air-borne dust inside and outside pig house.

(Sample sources of VOCs in solid and liquid phases, such as stored and fresh manure and pig wastewater, have also been studied.)

As part of the review Ni et al. (2012) reported on the characteristics of VOCs in air, in manure and in dust with respect to their abundance, spatial and temporal variations and source differences. (It should be noted, however, that abundance itself is not an indicator of importance for odour, as the odour threshold has also to be considered, e.g. using OAVs.) Ni et al (2012) reports, from two or more independent studies, the relatively abundant quantities of the following compounds in:

- **Air**: acetic acid, butyric acid, dimethylsulphide, dimethyldisulphide, isovaleric acid, p-cresol, propanoic acid, skatole, trimethylamine and valeric acid.
- **Manure**: acetic acid, p-cresol, isobutyric acid, butyric acid, indole, phenol, propanoic acid, isovaleric acid and skatole
- **Dust**: acetic acid, propanoic acid, butyric acid, valeric acid, p-cresol, hexanal and decanal.

For the characteristics of airborne VOCs, Ni et al (2012) cited several independent studies that demonstrated large VOC spatial variations due to dilution of the odour compounds emitted and dispersed from piggery locations. Zahn et al (1997) demonstrated, for most VOCs, a constant relationship of decreasing concentration with increasing distance (up to 100m) from the source A study by Koziel et al (2006) reported that odour downwind, up to a distance of 294m, was increasingly defined by a smaller number of odour compounds such as p-cresol. These strong odorants are mainly characterised by relatively low volatility, high molecular weight and high polarity. Wright et al (2005) reported an odour profile priority ranking for a pig finish site with source distance 250m. The top ranking was again p-cresol followed by 2-aminoacetophenone and 4-ethylphenol. The data reported by both Wright et al (2005) and Koziel et al (2006) did not include concentrations of the odorants identified. Despite the large amount of data on the analysis of the odour in pig houses or manure and slurry pits, very little concentration data on odour compounds downwind from the pig houses was accessible. There is a general lack of information on the concentrations of key odour compounds downwind from piggery units.

The increasing number of odour nuisance complaints against animal production sites has created strong scientific interest to establish appropriate science-based setback distances from the odour source. Some studies, Guo et al (2004), Jacobson et al (2005), Xing et al (2007) and Hoff et al (2008), have attempted to model the behaviour of the odour plume downwind in an attempt to predict its impact and help determine odour-annoyance-free setback distances from animal production sites. Under varying weather conditions, the presence of malodours can be detected up to 5 km from their source (Xing et al., 2007). Research by Sheridan et al (2004) used a dispersion modelling approach to determine the odour impact of intensive pig production in Ireland. Some of their main conclusions from the study were that the use of local meteorological data is critical and that biofiltration can play a significant role in odour impact reduction.

The sampling location can also interact with temporal variations of VOC concentrations with diurnal and seasonal variation reported by different researchers cited in the review by Ni et al (2012). The review cited work by Blunden et al (2005) who demonstrated seasonal variability of VOC concentrations at four different locations. However, temperature was not considered the primary or only determining factor in the VOC concentrations at the sampling locations.

Impact of method of collection and analysis

Laor, Parker and Page, (2014) recently published a detailed review comparing methodologies for odour measurement. The discussed the current limitations of many odour measuring techniques and overall concluded that recognising and quantifying these limitations would be a major step to improving the accuracy of odour measurements and much work was required to establish accurate measures of ‘odour’. Considerations for sampling include not only the specified locations where samples are taken but also the controlled time, interval, frequency, method and duration of sample taking and the regulation of the volume or sample mass to be delivered for analysis. The majority of published studies have used discrete sampling methods over set periods of time for example Ni et al (2009a). With this type of method, a representative sample of the VOC air is collected and followed by sample processing and analysis. The collection of airborne VOC samples is reliant upon an absorbent media, e.g., sorbent thermal absorption tubes with resins etc. or containers, e.g., tedlar sampling bags, canisters etc. Air samples are collected over a set time period either into sampling bags or on to sorbent tubes which are then transported to the laboratory for processing and analysis. Recent work by Trabue (2008) reported indications of a significant odorant bias in the use of tedlar bags for sampling. Some of the key malodours such as p-cresol and skatole when sampled and held in tedlar bags for 24 hours had recovery levels of less than 5% compared to those sampled by sorbent tubes. This would indicate that an inaccurate representation could have been reported in the literature for some of the VOCs in air samples taken from a piggery site and held for prolonged periods in tedlar bags before analysis.

The use of absorbent material can allow the sample to be moved over long distances and be stored for relatively long periods of time prior to analysis. Zahn et al (1997) showed that a combination of low volume sampling together with the use of sorbents

Tenax TA and Carbotrap C had an capture efficiency of VOCs greater than 92% at ambient temperature. Trabue (2008) reported that graphitised carbon sorbent tubes containing Carbopack X and Carbopack C had quantitative recovery of all compounds at all relative humidities and sampling volumes.

For the analysis of the collected gas sample, Hamon et al (2012) had a useful table in their review summarising the main techniques used for gas measurements in pig buildings along with their range of concentrations and accuracy of the method. Gas chromatography (GC) in combination with a specific detector such as mass spectrometry (MS) enables almost all compounds present to be accurately separated, detected and quantitatively analysed and is generally laboratory based as the instrumentation is usually non-transportable. This method of analysis, used in combination with an olfactometric method, has been widely reported by researchers in the literature Zahn et al (2001), Wright et al (2005), Yin-Cheung et al (2008), Trabue et al (2011) and Koziel et al (2006).

Olfactometry, is based on the use of human panels and an olfactometer (dilution equipment), and its main aim is to establish an odour's sensory characteristics in relation to three major parameters: concentration, intensity and hedonic value (Le et al., 2005).

- Odour concentration, measured by olfactometry, is expressed as odour units (OU) or odour units per cubic metre. One odour unit is defined as the amount of odour-causing gases which, when diluted in 1 cubic metre of air, can be detected from clean air by 50% of the members of an odour panel. This is the most commonly used parameter for signifying the strength of odour and a new standard method, EN 13275, to measure odour concentration by olfactometry has been completed by The European Standardisation Organisation CEN 2003.
- Odour intensity refers to the magnitude of the odour sensation and is measured by comparison to different but known concentrations of a standard reference odorant e.g. butanol. The relationship between odour intensity and logarithm of odour concentration is expected to be linear.

- Hedonic tone (value) is used to evaluate odour offensiveness. Human panellists indicate perceived hedonic value based on a nine-point hedonic scale ranging from pleasant to offensive on each sample presentation. There should be a linear relationship between the logarithm of the odour concentration and the hedonic value at that concentration.

Olfactometry, in combination with gas chromatography, evaluates the odour sensorily and chemically. The concentration of the odour is measured in odour units and by using gc-ms, the mass concentration of individual compounds of odour is quantified.

Other techniques for concentration measurement such as photoacoustic detection, fourier transform infrared spectroscopy (FTIR), (both suitable for continuous measurements) and colorimetry, (for occasional measurements), are all robust methods in terms of accuracy and stability. They are portable systems that can be used in pig buildings and field conditions for the quantification of the most abundant fixed gases such as ammonia, carbon dioxide and hydrogen sulphide. However, they are unable to detect some of the important odour compounds and, therefore, to characterise VOCs in terms of variations of source, concentration, composition and temporal factors Ni *et al*., 2009). Colorimetric tubes (draeger tubes) are very useful for occasional measurements to detect gas and odorant concentrations approximately and provide low-cost evaluation of the presence of compounds in air but these measurements appear to be less accurate than other methods such as gas chromatography

Chapter 3

Ammonia and Odour abatement techniques and their effectiveness

At the outset it is highlighted that approximately 50% of ammonia emissions are emitted from pig buildings which leaves the remaining 50% being emitted once the slurry leaves the building. As such as much emphasis is required 'ex building' to reduce ammonia emissions as is required within the building for an overall successful reduction in emissions. Webb *et al*. (2005) went as far as to say that applying slurry by band spreader or injection and covering slurry stores were more cost-effective measures to reduce emissions from pig production than applying techniques to reduce emissions from buildings (which included removing slurry frequently). However recent research has highlighted opportunity to reduce ammonia emissions from buildings which could complement reductions 'ex building'.

There is an abundant amount of information in the scientific and technical literature with regard to the many different techniques available for the minimisation and abatement of ammonia emissions from piggery locations but less so for odour. An overview of options for reducing odour emissions from pig production was provided by the EPA 1-84095-075-7 report (2001). The report gave detailed information on odour abatement methods including, where possible, indicative cost information for the installation and operation of the technology.

This review will outline abatement methods which could be applied to the three main 'areas' of ammonia and odour creation i.e. from the animal, due to house design above the slats and thirdly due to house design below the slats. Abatement methods with supporting peer reviewed scientific evidence of their effectiveness are outlined.

Chapter 3A : Abatement from the pig

Feed modification

Reduction in protein content on animal performance:

Reducing the protein content in the diet will reduce the amount of nitrogen excreted which will subsequently reduce the level of ammonia emissions. The mechanisms behind this are outlined below.

The efficiency of protein utilisation by pigs depends on the dietary composition and the physiological status or the growth stage of the animals. In growing-finishing pigs fed a cereal-soybean meal diet, about 32% of N intake is retained (Dourmad et al., 1999b). Faecal N excretion which amounts to 17% of the intake corresponds to the undigested protein fraction and endogenous losses. Digested proteins are absorbed as amino acids which are used for protein synthesis. Obligatory losses of amino acids relate to protein metabolism (turnover) and renewal of skin and hair. The remaining amino acids, after protein deposition and obligatory losses, are catabolised and excreted mainly as urea. With conventional diets, this last fraction is often the most important. Average efficiency of N retention is lowest in sows (20-30%), intermediate in growing pigs (30-40%), and highest in weaners (45-55%) (Dourmad et al.,1999a).

Two complementary nutritional approaches can be used to improve the efficiency of N utilisation in pigs and, consequently, to reduce N excretion. The first approach is to ensure adequate protein/amino acid supply over time according to the growth potential of the animals or their physiological state. This requires a joint fitting of daily supply of energy and protein (amino acids), depending on genetic potential and stage of production, and on production objectives. In fattening pigs, Latimier and Dourmad (1993) measured about 10% reduction in slurry N when different diets were applied during the growing and finishing periods, compared to feeding the same diet during both periods (Fig. 1).

The second approach is to improve the dietary amino acid balance and consequently reduce the required crude protein (CP) content of the diet. This can be obtained through a combination of different protein sources and/or the substitution of protein by inclusion of free amino acids. In fattening pigs, Dourmad et al. (1993) measured a 35% reduction of N excretion after improvements in the dietary amino acid profile without affecting feed intake, average daily gain, feed efficiency and carcass composition.

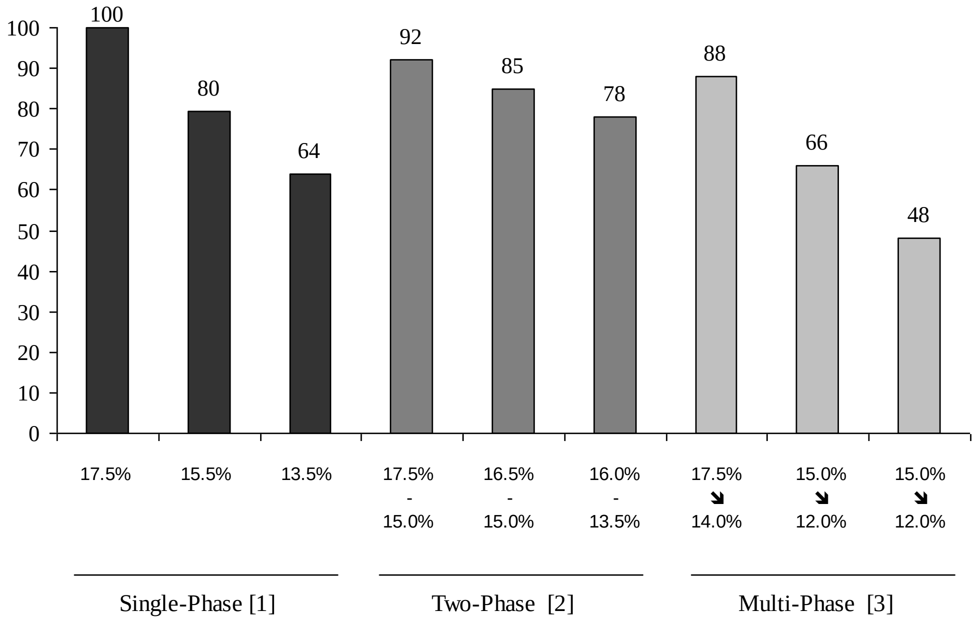

Figure 1. Effect of dietary protein content and protein feeding strategy on N excretion (100 = excretion with one-phase feeding of a 17.5% CP diet). Adapted from [1] Dourmad et al. (1993), [2] Latimier et al. (1993) and [3] Bourdon et al. (1997).

The ultimate reduction of N excretion can be reached when multiphase feeding is combined with a perfect balance between essential amino acids (close to the ideal protein concept), and with an optimisation of the supply of non-essential amino acids. Such a feeding strategy has been evaluated experimentally in fattening pigs by Bourdon et al. (1997). In that study, the use of a single diet (17.5% CP) over the whole growing-finishing period was compared to a “multiphase” strategy which consisted of the mixing of two diets (13.0 and 10.7% CP, re-equilibrated with free amino acids) in proportions that were optimised each week. Growth performance and carcass quality were similar, and N excretion was reduced by about 50% (1.83 vs. 3.56 kg N per pig) (Fig. 1). With this feeding strategy, N excretion represented only 50% of N intake.

It must be pointed out that the development of such feeding techniques for reducing N excretion by pigs requires good knowledge of the amino acid availability in feedstuffs, and of the changes in amino acid requirements according to growing stage or physiological state. This is now within reach with the use of modelling techniques for predicting requirements (NRC, 2012; van Milgen et al, 2008; Dourmad et al., 2008) together with a better knowledge of variations in amino acid availability in feedstuffs (NRC, 2012; CVB, 2000; INRA-AFZ, 2004). Moreover, more numerous amino acids are now available for feed use (lysine, methionine, threonine, tryptophane and valine) which allows a further reduction in dietary protein content. This can also be achieved in practice by using computerized blend feeding systems which allow adapting the diet composition on a daily or weekly basis (Feddes et al., 2000; Pomar et al., 2007). However, it should also be noted that it is often more costly to produce low crude protein diets (<15% CP) due to the increased requirement to include synthetic free amino acids and such 'precision'' feeding systems are currently very expensive to install.

Reduction in protein content on ammonia emissions

By changing feeding practices and reducing N excretion, it is possible to influence urea concentration in the urine and the pH of slurry, which will affect ammonia release (Van de Peet-Schwering et al., 1999). When pigs are fed low CP diets, urinary urea concentration and pH decrease (Canh et al, 1998; Portejoie et al, 2004). When water is available *ad libitum*, feeding low CP diets also results in lower urine production due to decreased water consumption (Pfeiffer et al, 1995; Portejoie et al., 2004). The changes in slurry characteristics result in lower ammonia losses during housing, storage and following application of slurry (Canh et al., 1998; Hayes et al., 2004; Portejoie et al., 2004; Jarret et al., 2011). For instance, in the study of Portejoie et al. (2004) ammonia emissions over the whole period from excretion to field application, was decreased by 63% when dietary CP was decreased from 20 to 12% in finishing pigs (Table 3). However ammonia emission was rather similar when expressed as a % of N excreted.

Overall there is a strong body of evidence which supports the impact of reducing the crude protein of the diet on the resultant ammonia emissions.

A detailed review by Webb *et al* (2014) collated results from six peer reviewed scientific papers, all of which undertook their experimentation using conditions similar to those present in Northern Ireland. Using the data from these papers Webb et al (2014) concluded that for every 1% or 10g/kg reduction in the dietary crude protein content for finisher pigs, ammonia emissions would reduce by 8%. Table 4 below summarises the results of these individual studies and more which have focused on the impact of reduced crude protein content on ammonia emissions. Philippe *et al*. (2006) also reported that a reduction of 8% in NH_3 emission per 1% lowering of CP was highly possible and these levels of reduction were in line with other studies which quoted reduction of between 8 to 13.3% per crude protein % unit (Canh *et al*. (1998); Hayes *et al*. (2004), Otto *et al*. (2003), Portejoie *et al*. (2004)).

Table 3 Effect of protein feeding of fattening pigs on slurry characteristics and ammonia volatilisation (Portejoie et al., 2004).

	Dietary crude protein content		
	20%	16%	12%
Slurry composition			
Amount (kg pig^{-1} d^{-1})	5.7	5.1	3.6
DM (%)	4.4	4.6	5.9
Total N (g N/kg)	5.48	4.30	3.05
Total ammoniacal N (g N/kg)	4.32	3.13	1.92
pH	8.92	8.61	7.57
N balance (g pig^{-1} d^{-1})			
Retention	23.2	23.5	21.9
Excretion	40.7	27.6	15.0
Ammonia volatilisation	17.4	13.8	6.4
Available to plants	23.3	13.8	8.6

Table 4. Pig characteristics, dietary treatments and results from peer reviewed scientific papers reporting effects of dietary crude protein on ammonia emissions.

Reference	Pig weight	Treatments	Ammonia emission	% decrease in ammonia per CP% unit
Kay and Lee (1997)	Grower 30-55kg, Finisher 60-90kg	Low CP : 15.2% (growers) and 13% (finishers)	78.9 g/24pigs/d (growers) 162.7 g/24pigs/d (finishers)	Growers: 65.9% reduction in NH_3 due to 5.4% reduction in CP level Finisher: 46% reduction in NH_3 emission from 5.7% reduction in CP
		High CP: 20.6% (growers) and 18.7% (finishers)	186.1 g/24pigs/d (growers) 301.3 g/24pigs/d (finishers)	
Hayes et al., 2004	70kg	13%	3.11	62.4% reduction in NH_3 emission from 9% reduction in CP
		16%	3.89	
		19%	5.89	
		22%	8.27 g/d/pig	
Portejoie et al 2004	50kg	12%	1.92 g N/kg (of slurry)	55% reduction in 'ammoniacal N in slurry' when CP reduced by 8%
		16%	3.13 g N/kg (of slurry)	
		20%	4.32 g N/kg (of slurry)	
Philippe et al., 2006	Grower 20-50kg, Finisher 50-	Low CP : 15.5% (growers)	14.35 g/pig/day	26% reduction in NH_3 emissions when Cp reduced by 3%

	120kg (26.6kg to 111.4kg in 118 days)	and 14% (finishers)		
		High CP: 18.1% (growers) and 17.5% (finishers)	10.60 g/pig/day	
Le et al 2009	57.7kg	12%	0.015 mg/s/m	28.6% reduction for a 3% reduction in CP
		15%	0.021 mg/s/m	
Leek et al., 2007	'Finishing pigs'	13%	2.38	62.7% reduction in ammonia emission over a 8% decrease in CP content
		16%	3.19	
		19%	4.94	
		21%	6.38	

Average ammonia emission and crude protein reduction across these studies

Across the studies above there was an average crude protein reduction of 6.5%. The average reduction in associated ammonia emissions was 68.7%. These studies and this calculation provides strong evidence that ammonia emissions can be reduced by 10% for every 1% reduction in crude protein level. Furthermore, these reductions were consistently experienced across broad ranges of dietary crude protein levels i.e 20% down to 12%.

Overall, utilising the information from peer reviewed scientific studies, peer reviewed reviews and data in Table 1 it can be advised, with much confidence that ammonia emissions will reduce by at least 8%, and highly probably by 10%, for every 1% reduction in the crude protein of growing and finishing pigs diets. Furthermore, this reduction is applicable to a broad range of dietary crude protein levels i.e. from 20% down to 12 % dietary and therefore the impact is additive (e.g. 8% shift in CP level would reduce ammonia emissions by at least 64% and possibly by 80%). Otto *et al.* (2003) using non commercial diets even found that ammonia emissions kept reducing when CP was reduced from 15% down to 0% CP.

Conditions under which current emission rates for ammonia are based.

The UK inventory for ammonia emissions (Misselbrook *et al*., 2000) outlines the ‘Housing emission factor’ (g N/500kg liveweight/d) for pigs of different categories on slats to be:

Dry Sows	17.0
Farrowers	29.5
Boars (straw bedded)	17.0
Fatteners <20kg	27.8
Fatteners 20 - 110kg	79.2
Fatteners >110kg	79.2

The Irish inventory for ammonia emissions also uses these values (Hyde *et al*., 2003). Misselbrook *et al*. (2000) outlines that the ‘pig’ emission factors were estimated from several studies namely Groot Koerkamp *et al*. (1998); Demmers *et al*. (1997); Peirson, (1995) and Phillips (unpublished data). The dietary details behind the ammonia emissions presented across these aforementioned papers was however lacking. As such it is not possible to comment with complete confidence the dietary crude protein levels contributing to the UK ammonia inventory. However, an investigative trail was followed which resulted in attaining reports and peer reviewed papers conducted within the same time period and within the same organizations, with similar aims, i.e. reducing ammonia and odour emissions. These reports and papers were mainly derived from ADAS (UK) work (e.g. MAFF report WA0632) and it was established both from them and personal communication (with an AB Agri representative who was a Dalgety employee during the 1990’s) that the diets used were called ‘Dalgety Optima 20/55’ (offered to 50kg) and ‘Dalgety optima

50’ (offered to finish). These diets had a crude protein of 21% and 18% respectively. In the MAFF report WA0632 ammonia emissions were measured as 79.2 g N/day/LU (500kg Liveweight) for finishing pigs using the aforementioned diets. The value is the same as that reported above in the UK inventory by Misselbrook *et al*. (2000).

In summary, although Misselbrook *et al* (2000) did not specifically note the crude protein levels used to derive the ammonia emission values it is suggested with confidence that diets containing 21% crude protein (offered to 50kg) and diets with 18% crude protein (offered from 50kg to finish) were used to establish the UK ammonia emission inventory for pigs.

As such the authors would suggest that these levels reflect responsible levels as the ‘starting point’ when applying the impact of abatement technologies.

Impact of diet on odour emissions from pigs

As indicated above odour is more complex since it is a combination of a range of gases and volatile compounds resulting from a number of sources e.g. hind gut fermentation in the pig to microbial breakdown of faeces (de Lange et al., 1999). Le *et al*. (2005) concluded that dietary protein (CP) and fermentable carbohydrates are the two key dietary factors involved in odour creation and their manipulation will alter odour emissions. However, the impact of dietary CP alone on odour emissions is conflicting where some dietary strategies have successfully reduced odour while others have not. However, there is a growing body of evidence which is enabling scientists to understand why and when odour emissions have been reduced or not and a growing body of evidence demonstrating success, albeit within a fixed range of CP.

When Hobbs et al. (1996) analysed individual gas compounds from pig odour they reported that the concentration of nine out of ten odorous compounds in the air was significantly reduced when low CP diets were fed to the pigs. In support of this, Hayes *et al.* (2004) reduced the CP of the diet from 19 to 16 to 13%, and subsequent odour emissions were reduced by 33 and 31% for the 16 and 13% diets respectively compared with the control diet of 19% CP. (Table 5 reports the diets used and impact on ammonia and odour). Furthermore Hayes *et al.* (2004) quote EPA 2002 by saying that 'the implementation of dietary manipulation in combination with other abatement techniques such as reducing the emitting manure surface area, frequent manure removal and improved ventilation systems could lead to a significant reduction in odour and ammonia emission rates.

On the other hand, Leek *et al*. (2007) when studying diets ranging from 21 to 13% CP found that the 'lowest' odour was emitted from 16% CP diets. Table 6 reports the diets used and resultant ammonia and odour emission reported by Leek *et al*. (2007). Using 'semi synthetic' diets which reduced the CP of the diet from 15 down to 0%, Otto et al., (2003) significantly reduced ammonia emissions but did not reduce odour offensiveness. Indeed in their study offensiveness was worse in diets containing 9 and 6% CP. (It should be noted that such diets would be commercially impracticable to make).

Complementary studies conducted by Le *et al*. (2007) and Le *et al* (2009) have provided some explanation why inconsistent results may arise between studies when reducing crude protein content. Le *et al.* (2007) found a reduction in odour as CP reduced from 18% down to 12%, but Le *et al.* (2009) found no such effect on odour when reducing from 15 to 12 % CP. Le *et al* (2007) commented that amino acid supplementation had the potential to alter the odour emission response and Le *et al.* (2009) suggested that no effect of CP level was found in their later study due to amino acid supplementation, especially sulphur containing amino acids. Previous to this Moeser *et al*. (2003) were able to significantly discriminate between diets differing in composition. The diets that yielded manure with the worst odour were high in sulphur (rich in garlic or feather meal), whereas a purified diet mainly based on starch and casein presented the lowest score (most pleasant).

Overall, Hayes *et al* (2004) and Le *et al* (2007) noted reductions in odour emissions when CP reduced from 19 and 18% respectively to 16 and 15% respectively (3% in each case). For Hayes *et al*. (2004) odour emissions reduced by 30% when moving from 19 to 16% (Table 5) (10% for every 1% shift in CP) and for Le *et al.* (2007)

odour emissions reduced by 58.5% (Table 7) when moving from 18 to 15% (19.5% for every 1% shift in CP) . Leek et al (2007) noted a quadratic response but there appears to be a clear reduction in odour emissions when moving from diets containing 19-21% CP to those containing 13-16% CP. This reduction is estimated to be 26% (Table 6) (4% for every 1% shift in CP).

Whilst Leek et al (2007) found that odour emissions continued to reduce when dietary CP levels fell below 16%, Hayes *et al* (2004), Le *et al* (2007) and Le *et al*. (2009) found no further reduction BUT importantly, odour emissions did not increase either. This would concur with Hansen *et al*. (2014) who found no positive or negative impact on odour emissions when dietary CP was lowered from 16 to 13.6%. Dourmad and Jondreville (2007) collaborates this statement.

Overall, using the body of current scientific evidence it is suggested that opportunity does exist to reduce odour emission through reduced crude protein content. However this opportunity only appears to be available when moving from a CP level of approximately 18.5% to a CP of approximately 15.5%. The level of reduction ranged from 19.5 to 4% for each 1% unit shift in CP. Therefore it is feasible to conclude that between CP levels of 18.5 and 15.5%, odour emissions could be reduced by 10% for every 1% decrease in dietary CP.   The current evidence would suggest that it is unlikely that further reductions in odour emissions would be realised by reducing crude protein lower than 15%.

However it is possible in the future that further reduction could be made using dietary manipulation if other dietary characteristics were investigated, especially those which manipulate hind gut fermentation (de Lange et al., 1999).

Increase in fermentable carbohydrate level:

Urea N excretion can also be reduced by including fibrous feedstuffs in the diet. Indeed Le et al (2008) concluded that the interaction between dietary CP and FC plays a crucial role in odour production and emission and that ammonia emission and odour from pig manure can be reduced substantially by decreasing dietary CP and by increasing FC in pig diet. With more fermentable non-starch polysaccharides (NSP) in the diet, some of the N excretion is shifted from urine to bacterial protein in faeces (Cahn et al., 1998; Kreuzer et al., 1998, Sørensen and Fernandez, 2003; Jarret et al., 2011, 2012), while total N excretion is not affected. Moreover, slurry pH is decreased with the use of fermentable NSP due to volatile fatty acid (VFA) formation in the hindgut of the pig and in the slurry. Cahn et al. (1998) measured a linear relationship between NSP intake and slurry pH or ammonia volatilisation; for each 100 g increase in NSP intake, the slurry pH decreased by 0.12 units and the ammonia emission from slurry decreased by 5.4%. This is consistent with the recent results obtained by Jarret et al. (2012) who compared two diets differing in their fibre content.

.

Table 5 Ingredients and analysed chemical composition of experimental diets and resultant ammonia and odour emissions (Hayes *et al.* (2004))

Diet (Crude protein (g/kg))	**220**	**190**	**160**	**130**
Ingredient inclusion (kg/t)				
Wheat	637.5	722.5	810.0	887.7
Soya bean meal	309.2	224.2	136.7	60.0
Soya oil				13.3
DeviCare® Supplement[a]	25.0	25.0	25.0	25.0
Amino acid pack[b]	15.0	15.0	15.0	15.0
Analysed composition (g/kg)				
Dry matter	873.2	875.1	873.0	877.1
Crude protein	209.0	184.6	157.4	131.7
Crude oil (ether extract)	29.4	26.9	27.3	33.0
Crude fibre	38.4	39.1	36.4	29.3
Ash	53.2	48.9	46.4	38.2
Gross energy (MJ/kg)	15.98	15.82	15.52	15.81
Relative cost index[c]	1.00	1.05	1.15	1.30
Ammonia emission rate (g/d/animal[1]	8.27^{c}	5.89^{bc}	3.89^{b}	3.11^{a}
Odour emission rate (OUe/s/animal)[2]	17.6	19.6	13.2	12.11
Odour emission rate (OUe/s/LU)[3]	102.9^{b}	115.8^{b}	80.0^{a}	77.6^{a}

[1] s.e. = 0.509 (N=60); P=0.001, [2] s.e. = 1.5 (N=60); P=0.005, [3] s.e. = 0.8.1 (N=60); P=0.009

[a] The supplement (DeviCare, Devenish Nutrition, Belfast, N. Ireland) provided minerals and vitamins (per kg diet) as follows 14,000 i.u. Vitamin A (4.2 mg retinol), 2,800 i.u. Vitamin D (0.07 mg cholecalciferol), 80 iu. Vitamin E (80 mg DL-alpha tocopherol), 120 mg copper as copper sulphate and 0.4 g selenium as sodium selenite.

[b] The amino acid pack contained supplementary synthetic lysine to maintain a dietary lysine content of 11 g/kg, and synthetic methionine, threonine and tryptophan on calcium carbonate carrier maintaining minimum dietary levels of 60%, 65% and 20% methionine + cysteine, threonine and tryptophan, respectively, and relative to lysine in the finished diet.

[c] The relative cost of each diet was estimated according to raw material prices at time of publishing and is largely influenced by the additional cost of synthetic amino acid use in low protein diets. The costs of both soybean meal and synthetic amino acids are influenced by market conditions, which will impact the accuracy of this index.

Table 6 Ingredients and proximate composition (as fed) and resultant ammonia and odour emissions (Leek *et al.*, 2007).

Formulated crude protein concentration (g/kg)	**130.0**	**160.0**	**190.0**	**210.0**
Ingredient inclusion (g/kg)				
Wheat	886.7	810.0	722.5	637.5
Soya bean meal	60.0	136.7	224.2	309.2
Soya oil	13.3	13.3	13.3	13.3
Amino acid pack[a]	15.0	15.0	15.0	15.0
Vitamin and mineral pack[b]	25.0	25.0	25.0	25.0
Composition (g/kg)				
Dry matter	875.7	870.1	877.0	872.9
Crude protein (N x 6.25)	133.2	157.4	190.0	206.4
Ash	38.6	48.3	49.2	51.1
Crude fibre	13.3	24.7	29.5	27.6
Ether extract	31.1	26.4	28.3	28.6
Starch[c]	512.9	472.9	427.1	382.6
Gross energy (GE, MJ/kg)	15.73	15.63	15.79	15.88
Ammonia emission rate (g/d/animal[d]	2.38	3.19	4.94	6.38
Odour emission rate (OUe/s/animal)[e]	10.17^{bc}	8.65^{b}	11.73^{cd}	13.8^{ad}

[a] The mineral and vitamin premix (Devenish Nutrition, Belfast, N. Ireland) provided (per kg feed): 6000 IU vitamin A, 800 IU vitamin D_3, 60 mg vitamin E, 1 mg vitamin K, 2 mg thiamine, 3 mg riboflavin, 10 mg pantothenic acid, 2 mg pyridoxine, 15 mg nicotinic acid, 2 g phosphorus as mono dicalcium phosphate, 6 mg copper as copper sulphate, 100 mg iron as ferrous sulphate, 100 mg zinc as zinc oxide, 0.2 mg selenium as selenomethionine, 10 mg manganese as manganese oxide and 0.2 mg iodine as calcium iodate on a calcium sulphate/calcium carbonate carrier.

[b] The amino acid pack contained supplementary L-lysine HC1 to maintain a total dietary lysine concentration of 11 g/kg and DL-methionine, L-threonine and L-tryptophan on a calcium carbonate carrier providing total dietary levels relative to lysine of 60% methionine + cysteine, 65% threonine and 20% tryptophan.

[c] Calculated concentration. [d] linear effect P<0.01, s.e. 0.615

[e] Quadratic relationship (P<0.01), s.e. 0.838. Values with different superscripts are significantly different (P<0.05)

Table 7 Ammonia and odour emissions as reported by Le *et al.*, 2007 and 2009.

	Le et al 2007					Le et al 2009		
Dietary CP:	**12%**	**15%**	**18%**	**P**		**12%**	**15%**	**P**
Ammonia emission (mg/s/m^2)	0.008	0.009	0.017	<0.05		0.015[a]	0.021[b]	0.03
Odour emission (oue/s/m^2	1.03	1.85	4.46	<0.05		0.67	0.65	0.88

Conditions under which current emission rates for odour are based.

The standard emission factors used by NIEA are shown in the Table below. These are the same as those used by the Environment Agency (2003) and the EPA (2001). The emission factors contained in the Netherlands 2006 Regulation are also accepted in appropriate circumstances.

NIEA Odour emission rates assumed for pigs:

Category of animal/housing type	Recommended emission factors OU_E/sec/animal
Fatteners, conventional, partly slatted	22.5
Fatteners, restricted emitting area below slats	10
Fatteners, cooling of slurry surface below slats	11
Fatteners, flushing twice/day below slats	11

Summary of reported emission factors for pigs

	Dry Sows OU_E/sec/pig	Farrowers OU_E/sec/pig	1st Stage Weaners OU_E/sec/pig	2nd Stage Weaners OU_E/sec/pig	Finishers OU_E/sec/pig
Hayes[a]	10.9 – 24.1	33.2 – 66.4	3.7 – 4.6	9.3 – 10.5	10.7 – 28.8
EPA[b]	19.0	19.0	6.0	6.0	22.5
Netherlands[c]	19.0	17.8	5.0 – 16.3	5.0 – 16.3	22.4
Belgium[d]	44.6	17.2	3.3	3.3	25.4
UK[e]	N/A	N/A	N/A	N/A	18.7 – 36.1

(a) Hayes et al (2005); (b) EPA (2001); (c) Ogink & Groot Koerkamp (2001); (d) van Langenhove & De Bruyn (2001); (e) Peirson & Nicholson (1995)

The following outlines the methodology used in the papers above to establish the emission factors for finisher pigs:

	Brief outline	Diet	Age/weight of animal	Number of samples taken	Odour measured by
Hayes[a]	4 pig units used, all fully slatted, 3 had negative mechanical ventilation, one had ACNV	Unit 1 – details not given, Unit 2, 3 and 4 17% CP	Finishers are over 35kg	Units sampled over a 2 yr period Eight odour samples collected from one finisher house per unit over a 5 week period.	EN 13725 (CEN 2003

EPA[b] (pg 48/49 of report)	Data really taken from Netherlands paper below but balances with other data to arrive at a recommendation of 22.5 for finishers				EN 13725
Netherlands[c]	1)Conventional – partially slatted floor 2) Restricted emitting surface below the slats 3) cooled surface of stored slurry below slats 4)flushing system below slats, operated twice daily 5) air scrubber, acid liquid, animals conventionally housed	Details not given (but EPA report indicates work completed between 1996 and 1999 although work seems to have been first reported in 1997!)	Not clear but suggests animals were 85-110kg	Two successive fattening rounds (16 weeks each) were sampled. A total of 10 odour samples (5 per round) were taken in duplicate (therefore 20 per house type) evenly distributed over the period of 16 weeks	Dutch system NVN2820/1A
Belgium[d]	Conducted between 1999 and 2000.	Details not given	Not given	Seems to be two sampling periods (one is spring/summer, the other is autumn/winter).	CEN, 2000 (Sniffing teams)

				17 months? ‘measurements’ = 20 – but not sure if this is different parameters or replicates	
UK[e]	EPA report indicates that data collated between 1987-1995. But apparently most of the data were collected late1992/early1993	No details	No details	Took samples on the back of two dietary trials, one enzyme based and on CP/N based. Spot measurements taken on CP?N trial, series measurements taken on enzyme trial. No. of observations range from 1 to 13 (pg 7) although 34 in total if combined for all ventilation rates for fully slatted	Used Dutch NVN2820 method but data were converted to ‘European odour unit’

(a) Hayes et al (2005); (b) EPA (2001); (c) Ogink & Groot Koerkamp (2001); (d) van Langenhove & De Bruyn (2001); (e) Peirson & Nicholson (1995)

NB in the EPA report – Part B they describe a ‘limited’ study to make an assessment of odour from Irish pig fattening units. They used 2 farms, and took triplicate samples for four ‘groups of fatteners’ (12 samples in total) from each farm. EPA used these results to support the adoption of 22.5 as the recommended odour emission rate.

Like ammonia there was a lack of information on dietary formulations and compositions but through deduction of studies published at this time, especially by MAFF/ADAS it is highly probable that the values above are based on diets containing 20-21% crude protein for growing pigs (approximately 30 to 50kg) and 18% crude protein for pigs from 50kg to finish.

Conclusion

From the above discussion and published research, a balanced inclusion of crude protein and fermentable carbohydrate in pig diet is essential to reduce ammonia and odour emissions from pig production. The nutritional strategy should involve lowering crude protein intake in combination with supplementation of limiting amino acids and shifting nitrogen excretion from urine to faeces by including fermentable carbohydrates in the diet. Aarnink and Verstegen, (2007) suggested that by combining different strategies a total reduction of ammonia and odour emission in growing-finishing pigs of 70% could be reached but more research is required in this area.

Other feed manipulations affecting ammonia emissions

Other than balancing crude protein and fermentable carbohydrate levels in diet, adding different feed additives to the pig diet is also gaining popularity in reducing ammonia and odour emissions. Commonly researched additives found in literature include; non-starch polysaccharides enzymes, acidifying salts and dietary electrolyte balance, yucca extract, zeolites and probiotics. Some additives have shown better results than others in reducing ammonia after incorporation in feed and manure. Factors of importance to consider before additive inclusion include cost effectiveness, effects on performance, ease of availability and effects on other feed components.

The electrolytic balance (EB), calculated as (Na^+ + K^+ - Cl^-), is often used by nutritionists to evaluate the acidogenicity of the diet. A decrease in the EB will result in a decrease of urinary pH. When dietary CP content is reduced, EB also decreases because of the high K content of most protein sources. This partly explains the effect of CP on urinary pH. However, as shown by Cahn et al. (1998), more drastic changes in urinary pH and ammonia volatilisation can be obtained by inclusion of the Ca salts ($CaSO_4$ or $CaCl_2$ instead of $CaCO_3$). The addition of Ca-benzoate (Cahn et al., 1998) or benzoic acid (Guingand et al., 2005; Guiziou et al., 2006) has also been found to be effective in reducing slurry pH and ammonia volatilisation (by 25 to 40% (Daumer et al., 2007)), because these products are metabolized into hippuric acid which is rapidly excreted in urine. A similar effect (25% reduction in ammonia emission) was observed with adipic acid (van Kempen, 2001) which is partially excreted in urine. However, cost-effectiveness of benzoic acid inclusion is low. For 10% NH_3 reduction, Aarnink et al. (2010) estimated the costs per place per year as 6.2€ for benzoic acid inclusion and about 2€ for $CaCO_3$ exchange by $CaCl_2$ or $CaSO_4$.

Philippe et al., (2011) reviewed different additives and their effectiveness in relation to performance and ammonia reduction. While a mixture of β-glucanase and β-xylanase when added as an enzyme supplement to the diet improved digestibility and performance, contrasting results were found by Garry et al., (2007) and Leek et al., (2007) for NH_3 emissions according to cereal type. Although, enzyme supplementation in the wheat based diet decreased NH_3 emissions by 15–20% (Garry et al., 2007), barley-based diets with enzyme supplementation increased NH_3 emissions by 30% (Garry et al., 2007; O'Shea et al., 2010). In contrast, with oat-based diets, O'Shea et al. (2010) did not observe any effect of enzyme inclusion on NH_3 emissions. With regard to the use of probiotics, contradictory outcomes have been observed across the limited studies completed (Philippe et al., 2011).

On the other hand yucca extract and zeolites could decrease ammonia emissions and increase performance and health status. The effect of Yucca extracts is considered to be associated with glyco-components of its sap, especially saponins. Researchers (Colina et al., 2001) have suggested that these components, with dietary inclusion of 0.01% of the extract, inhibit urease activity and chemically convert or bind NH_3 leading to reduction in ammonia emissions ranging from 20 to 30%. Additionally, direct application to manure has also shown reduction in ammonia emissions (Panetta et al., 2006). Addition of zeolites (microporous aluminosilicate minerals characterized by large internal surface area and high cation exchange capacity) to the pig diet has shown promising results. Zeolites exist naturally and have an affinity towards various cations. Studies have shown a reduction in NH_3 emissions by 33% when piglets were fed 2% zeolites supplemented diet (Milic et al., 2006).

Chapter 3B: Housing design above slats

There are numerous 'housing design' factors that can influence ammonia and odour emissions. These include type of flooring, type and design of slat, type of bedding used, ventilation system, humidity and temperature variations and control, use of air and bio-filters, slurry pit design and manure treatment. The following paragraphs report in more detail their impact and efficacy when abating ammonia and odour emissions.

Slat design and make

Pigs are usually kept on concrete slatted floors with a slurry pit underneath. Good drainage of manure through the floor is essential to limit fouled areas that are significant sources of NH_3 (Svennerstedt, 1999). Type of flooring and slat design significantly affects the drainage of manure. Svennerstedt (1999) reported that trapezoidal cross section slats perform better and favour drainage. Additionally the use of slats with notches or protruding edges gave better results in favouring manure drainage. Svennerstedt (1999) also concluded in his study that enlarging gap widths, from 2 to 30 mm, decreases emission by more than 50%. Hamelin et al., (2010) showed similar findings in agreement with Svennerstedt (1999) that the presence of a notch results in average emission reductions between 23 and 42% compared with the control design typically used in pig houses. However, Hamelin et al. (2010) did not find any significant differences for the NH_3 emissions in relation to slat crosssectional shape. They also found the presence of an epoxy coating contributed no significant differences to the NH_3 emission that was reported in the past by Pelletier et al., (2005).

Another area of research linked to slatted floor system is substituting concrete floors by plastic and other metals. Studies have shown a reduction in ammonia emissions by 10–40% when concrete slats were substituted with cast iron metal or plastic slats (Aarnink et al., 1997; Timmerman et al., 2003; Pedersen and Ravn, 2008). However, there are concerns for the use of plastic slats as they are not recommended for heavy pigs. In addition, metal slats are associated with skin, limb and foot lesions resulting in adverse performance and animal welfare issues (Lewis et al., 2005). Furthermore, the cost of these materials is significantly higher than concrete.

Part slatted flooring and bedding

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

Hamon et al (2012), reported that the literature gave conflicting evidence for ammonia emissions when using litter and slatted flooring but contrary to the above, they concluded that in general ammonia emissions were greater when using a partially slatted floor, due to the soiling of the solid floors reflecting the difficultly to manage pigs to avoid such soiling. In a review by Philippe et al., (2011) partly slated flooring resulted in lower emissions provided that solid floor remains clear of manure. However seasonal changes and climatic conditions can influence animal behaviour resulting in high ammonia emissions from solid floor. During summer and hot days, pigs tend to soil the solid floor and spend more time on it to minimise heat stress associated with high animal density, inadequate space and hot conditions, as mentioned.

For the past few decades, bedded systems have met renewed interest, as they are related to improved welfare, and a better brand image of livestock production. However, this technique is associated with increased cost principally due to the straw use and the labour for litter management even if building costs are usually reduced (Philippe et al., 2006). For existing buildings, this system can be quite easily applied for housing with concrete solid floor, but no so for slatted systems.

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

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

Gilhespy et al., (2009) investigated the role of additional straw bedding in reducing ammonia emissions from pig and cattle housing. His research team used a combination of wheat (Triticum aestivum) and barley (Hordeum vulgare) straw incorporated at a conventional rate and they observed ammonia emissions of 42%. It has been suggested that the addition of litter materials increases the C/N ratio and the aeration of the manure, which favour the bacterial growth and the N assimilation into stable microbial protein resulting in lower NH_3 and N_2O emissions (Dewes, 1996; Sommer and Moller, 2000). However Gilhepsy et al., (2009) observed that an increase of 100% straw broadcast over the entire floor, reduced NH_3 emission from cattle by 20%, but greater addition beyond that did not give any further significant reduction. Thus his findings suggested optimum results may be obtained from the addition of 100% extra straw broadcast over the whole floor for pigs because fluctuating temperatures in buildings housing pigs lead to them changing their pattern of dunging and urinating and hence an overall addition of straw is needed in order to ensure that extra straw is provided over all the potential area for excretion

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

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

Groenestein et al., (2006 and 2007) had similar concluding remarks as of Gilhepsy et al., (2009) above in that motivated by climatic conditions, pigs lying and urinating behaviour on straw or solid floor significantly influence ammonia and odour emissions from pig houses. Groenestein et al., (2007) found that although the straw bed was 60% of the emitting surface area, it only contributed 27% to the emission from the entire sow house, because of the low number of urinations per m^2 and the relatively low emission from a urine pool in the straw bed. On the other hand, the alley contributed 42% highest of the total emission, even though it accounted for only 23% of the total emitting area. Groenestein et al., (2006) also showed the importance of urinating behaviour when discussing the full-house emission and the relative contribution of each emitting substrate to the emission from the entire house. When samples were collected from different areas (concrete floor, slurry pits, waiting area and straw bedding), results revealed that in a sow house with straw bedding, the largest source of ammonia emission was a urine puddle on the concrete floor in the walking alley and the smallest was a urination on straw. Results by Groenestein et al., (2006) appeared to show that the straw bedding reduces ammonia only when urination occurs on straw bedding. Therefore, the distribution of urine puddles is an important factor when discussing emissions from piggery houses.

Considering the issues associated with straw bedding like increased cost, labour and variations in urinating behaviour, Philippe et al., (2012) compared the emissions of NH_3, nitrous oxide (N_2O), methane (CH_4) and carbon dioxide (CO_2) during the fattening of pigs kept on straw-based deep litter or on straw-flow system. The reason cited for using the straw flow pen was that when the straw mixes with the dung, it will travel down the slope by pig motion and go out of the pen to a scraped passage, with the result less labour is required making it more cost effective. Even though fattening pigs were kept in a straw flow pen, the gaseous emission measurements were significantly lower for NO (−55%), CH_4 (−46%), CO_2 equivalents (−47%), CO_2 (−10%) and H_2O (−23%) compared to pigs housed on straw-based deep litter. However, gaseous emissions were significantly greater for NH_3 (+10%). In the current experiment as discussed by Philippe et al., (2012), the separation of the liquid fraction of the manure from the scraping passage did not prevent rapid NH_3 synthesis from the soiled surface of the pen leading to high ammonia emissions. Moreover, daily manipulation in scraping solid manure might have favoured NH_3 emissions by aeration, as described by Gibbs et al., (2002).

Philippe et al., (2011) also reviewed several bedding materials with regard to emissions. According to his review, sawdust and a combination of wood shaving and peat could be used as a replacement for straw. Philippe et al., (2011) concluded in their review that ammonia emissions from sawdust-based deep litter seem to be lower than from straw-based deep litter. However, they also found that N_2O emissions are higher with sawdust. Similarly, such an increase in N_2O emissions associated with a decrease in NH_3 emissions was also observed by Nicks et al., (2004) when comparing gaseous emissions from deep litter pens with straw or sawdust for fattening pigs. The use of the alternative option of a mixture of peat and straw showed a reduction in ammonia emissions by 60% with a mixture of peat (60%) and straw (40%) when compared to straw in a naturally ventilated deep litter house for fattening pigs, (Jeppsson, 1998). Whatever bedding material is opted for use, the important factors to consider are its cost effectiveness by requiring less labour and the issue of animal welfare as well as product safety.

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

Unfortunately there is a lack of information comparing straw based systems with part of fully slatted systems.

Acid scrubbers and bio filters:

Other efficient ways of reducing odorous compounds, smell and ammonia from piggery houses include the installation of air scrubbers' that can effectively remove odours compounds from the exhaust air. There are two main types of air scrubbers: acid scrubbers and biofilters. Acid scrubbers contain media consisting of inert or inorganic material (scrubber) while biofilters, on the other hand are a mixture of compost, wood chips, peat, soil or rockwool (Melse et al., 2009; Yasuda et al., 2009).

In an acid scrubber sulphuric acid is used generally to maintain pH of the recycled water below four. For a biofilter, the media is inoculated with specific aerobic microorganisms in order to transform inorganic compounds or to break down organic compounds (Deshusses, 1997). Melse and Mol., (2004) studied odour removal from pig house exhaust air by a biotrickling filter. Ammonia and odour removal efficiency observed were on average 79% and 49% respectively. The efficiency of the removal of odour from the exhaust air of the pig house showed a large variation in this study that according to Melse and Mol was due to operating the biofilter below its maximum absolute odour removal capacity. Biofilters should be designed to consider the provision of optimal conditions for the growth of essential bacteria within the biofilter. These bacteria degrade the odorous compounds to less odorous end products (Powers, 1999). If proper design and management is achieved then there is a possibility that low-cost bio-filtration systems can be implemented in livestock housing facilities. However, it needs further research and investigation into design and management involving manufacturers, farm workers and proper training of personnel involved.

It is observed that effectiveness of air scrubbers in reducing ammonia and odour largely depends on inlet NH_3 concentration, residence time, moisture content, temperature, oxygen (O_2) level, pH and media characteristics (Chen et al., 2008; Melse et al., 2009). These are factors to consider while designing and implementing any scrubber system. Data from finishing pig houses presented NH_3 reductions ranging from 65% to 95% with the two types of air scrubber. Implementation of this system is expensive as it not only includes installation but also filter maintenance costs, and operational costs associated with energy cost and chemicals involved (Melse et al., 2009). Therefore, improving the cost-efficiency of air scrubber is crucial to promote the system.

Another available option is combining the concepts of different scrubbing and filtering systems in one system designed to reduce ammonia emissions and reduction of odour and particulate matter. A new development in this concept is the application of multi-pollutants scrubbers. Multipollutant scrubbers are multi-stage systems and each stage targets the removal of one type of compound. Multipollutant scrubbers could be a solution to ammonia and odour, however, further research and development is necessary to keep investment and operational costs at an acceptable level (Melse et al., 2009).

An alternative method which is cost effective though less efficient to air scrubbers may be provided by the use of filters, with fibrous filters the most common type. Fibrous filters function by entrapping dust and associated odour-causing compounds. It is seen that traditional filter systems operating in broiler houses reduce dust content by up to 50%. However, drawback associated with this system is that the filters easily undergo clogging (dust and feathers): thus, the required maintenance of filters can become quite time consuming and tedious. For this reason, poultry operators prefer air conditioning units rather than fibrous filters (Powers, 1999).

Biofiltration and Biotrickling filtration

As mentioned, the biofiltration system generally uses natural materials such as wood or peat as the filter filling material which allows the growth of microorganisms participating in the reduction of the pollutants. Hamon *et al*. (2012), in their review on odour abatement methods, considered biofiltration to be the most cost-effective technology for treating the ventilation exhaust air from animal housing and critical to the success of wood-chip based biofilters is the maintenance of proper moisture content. The biotrickling filtration method uses only inorganic materials as filters with the water flow made by continuous percolation. This, according to Deshusses and Gabriel (2005), is a promising new technique for controlling odour and VOCs. In a systematic literature review to identify an air contaminant removal technology for pig house exhaust air Lemay *et al*. (2009) found that various configurations of biotrickling filters and bioscrubbers show good potential for odour emission control but have not been the subject of many experimental studies on a full-scale system. They conclude that a combination of air treatment technologies - mechanical filtration, air scrubber and biotreatment - have a high potential for application.

Wet/Air Scrubbers and Bioscrubbers

The review by Hamon *et al.* (2012) noted that the wet/air scrubbers were very useful for ammonia removal, with an efficiency level between 60% and 80% but the method is very selective for only acidic or basic compounds. Indeed, since ammonia and hydrogen sulphide have completely opposite solubility, it is impossible for this technology to treat these two gaseous pollutants simultaneously. Bioscrubbers function like wet scrubbers but with the inclusion of a bioreactor to enable post-treatment. The performances of such a system are comparable to those of wet scrubbers.

Other factors:

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

Chapter 3C: Housing design below slat

With regard to slurry storage, the traditional way of storing slurry is to store manure under the slats. Slurry could be stored here for up to three or four months before extraction for spreading or to an outside tank. This traditional system leads to a continuous source of ammonia and odour emissions from the pit. Therefore, several manure management strategies on slurry pit designs were developed to mitigate emissions. These include segregation of urine and faeces and frequency of manure removal via scrapping or flushing.

Segregation of urine from faeces:

With regard to tank design, one of the most reviewed and effective strategies of reducing emissions is via the V shaped scraper system which segregates urine from faeces. This system involves a channel with two inclined surfaces on each side of a central gutter. Thanks to a longitudinal slope of around 1%, the liquid fraction continuously runs off by gravity towards the gutter before being redirected outside the building. The solid fraction remains on the inclined surface before being scraped several times a day (Godbout et al., 2006). By the installation of an under-slat V-shaped scraper, reductions around 40-50% were achieved for NH_3 and N_2O, and around 20% for CH_4 (Godbout et al., 2006; Lagadec et al., 2012). In the review by Philippe et al., (2011) they noted reductions of around 50% could be achieved by using the V shaped system when a 1% slope was used. Moreover, if the slope was increased from 1% to 3%, emissions can be further reduced by 17%.

Ye et al., (2007) found that increasing the slope gradient increased construction costs however they found that a slope gradient of 20% with a surface coated with fine cement performed best. His results also concluded that in combination with a slope gradient of 20%, the lowest percentage of faeces drainage and good urine drainage performance was obtained by a concrete slatted floor with 5mm-wide gaps and a trapezoidal profile without sharp edges.

Conveyor belts are also an effective system to separate urine from faeces under slats. They are composed of a perforated belt through which the liquid percolates into a conventional pit whereas the faeces left on the belt are conveyed out of the pen into a separate collection pit (Lachance et al., 2005; Pouliot et al., 2006). With this system, authors reported reductions of NH_3- and CH_4-emissions around 50% and 20%, respectively, in comparison with conventional storage systems (van Kempen et al., 2003; Godbout et al., 2006).

Using a 'V-Belt' systems De Vries et al., (2013) showed a reduced impact on gas emissions by up to 82%, due to lower methane and ammonia emissions. Other authors have also reported reductions of ammonia emissions of around 50% in comparison with conventional storage systems when using V shaped scrapper system (Kaspers et al., 2002; Koger et al., 2002; van Kempen et al., 2003; Lachance, 2005). The efficiency of this system is linked to the minimal contact time between urea and faecal microbes. Furthermore, the separation aids recycling and treatment of manure. Segregation of urine from faeces is considered a highly effective method and this is evident from a number of studies.

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

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

Frequency of manure removal from under slat pit systems:

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

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

Slurry treatment

Recent work by Bildsoe *et al.* (2012) reported that low dosage ozonation is useful for reduction of emissions of hydrogen sulphide from pig slurry but higher doses increased the emission rate of ammonia due to a pH change at the slurry surface.

Chemical treatment:

Physical and chemical treatment of slurry could also reduce ammonia and odour emissions from piggery and livestock systems. Smith et al., (2004) studied the use of a combination of manure treatment and dietary intervention to reduce ammonia from piggery systems concluding that dietary manipulation with phytase and application of aluminium chloride ($AlCl_3$) to manure were promising management practices for the reduction of NH_3 from swine facilities. When Aluminum chloride was added to manure pits at 0, 0.25, 0.50, and 0.75% $AlCl_3$ on a volumetric basis, it lead to a decrease in manure pH resulting in decreased ammonia losses. As for dietary manipulation, Smith et al., (2004) investigated two phytase treatments: 1) normal diet without phytase and 2) phytase mixed into feed after pelleting at 500 U of phytase/kg of feed. The results of the study found that use of both dietary phytase and aluminum chloride manure amendments decreased manure pH and ammonia losses by 54%. Thus, phytase could be effective at decreasing ambient ammonia levels if dose is optimised for inclusion in the management practices. Additional benefits other than the reduction in ammonia levels include improved production because of reduced susceptibility to respiratory ailments resulting in increased feed intake and average daily gain as observed by Smith et al., (2004).

Slurry Additives.

The review by Hamon *et al.* (2012) reported the addition of nitrates or molybdates to reduce hydrogen sulphide emissions in slurry and also the addition of peroxides to reduce the generation of odorant compounds. By increasing the pH of the manure (the optimal growth pH is between 6 and 8), the growth of odour-producing bacteria can be reduced (Zhu, 2000).

A study by Kim *et al*. (2008) revealed the odour intensity and offensiveness lessened by spraying artificial spice and essential oils, of which the maximum reduction rates ranged from 60% to 80%. Moreover essential oils do not only mask odorants but are antimicrobial agents useful in reducing sulphurous compounds.

Manure spreading technique:

Although the addition of additives to manure and feed can result in lower ammonia emissions, the technique involved in spreading or incorporating slurry on to arable land can also significantly affect NH_3 emissions from slurry as shown by Carozzi et al., (2013). Carozzi et al., (2013) found that when slurry was directly incorporated into the soil, the NH_3 emission process was exhausted in the first 24–48 h after slurry spreading. Carozzi et al., (2013) concluded that slurry incorporation directly into soil lead to reductions of up to 95% with respect to the surface spreading. The faster the incorporation after the slurry spreading, the higher were the benefits in terms of reduction of NH_3 losses. Although this study looked into cattle slurry spreading and incorporation techniques, it is a good indicator of the benefits of slurry incorporation that could be introduced in piggery slurry management practises. Carozzi et al., (2013) also highlighted that NH_3 emission is also strongly affected by the soil and weather conditions at time of slurry application where low values of wind speed, soil and slurry pH strongly affects NH_3 volatilization. Therefore weather conditions must also be taken into account in order to further decrease N losses via NH_3 volatilization.

Slurry coverings:

Manure storage pits are usually outdoors and cause strong odour nuisances. From the different available methods of reducing nuisance odour and ammonia emissions from pig slurry, one of the most commonly used methods is the application of different floating covers on slurry. Covering of the slurry affects both ammonia and carbon dioxide gaseous exchange with free air because it modifies the slurry surface pH and also acts as a physical barrier. A study by Guarino et al., (2006) investigated the effectiveness of five simple floating covers in reducing emissions from pig and cattle slurry. Guarino et al., (2006) tested vegetable oil (a mixture of rapeseed and soybean oil), expanded clay, chopped maize stalks, chopped wheat straw, and chopped wood chips as different slurry coverings. His research team revealed substantial differences in ammonia emission reduction efficiency (1% to 100%) and odour abatement (0% to 90%). It is also worth mentioning that high levels of reduction efficiency were observed with a greater thickness of the used covers. The best results were achieved with vegetable oil (79.5% to 100%). However, with regard to floatation aptitude and cover deterioration on slurry, expanded clay and wood chips demonstrated long-term resistance to both deterioration and sinking. This study demonstrated that simplified covers can offer an alternative to costly and complex rigid covers and could be practicable and effective (Guarino et al., 2006).

A review by VanderZaag *et al.* (2008) outlined the use and effectiveness for odour abatement of covers of natural origin - natural crusts, straw, peat, and clay aggregates and synthetic origin – geotextile, plastic and rubber and composites of both. Nearly all cover types were capable of substantially reducing ammonia emissions (compared to uncovered controls). Reductions of odour including hydrogen sulphide have also been good, though fewer cover types have been assessed with respect to these parameters.

Slurry treatment model:

Szogi et al., (2006) designed a slurry treatment model to study changes in NH_3 emissions as a result of improved water quality. This model combined treatment technologies consisting of solid-liquid separation in lagoons with removal of nitrogen and phosphorus from the liquid phase treatment system, recovering the manure solids and replacing the anaerobic lagoon liquid with cleaner water e.g. anaerobic lagoon conversion into a treated water pond. The results showed that lower nitrogen (N_2) concentrations in the converted lagoon substantially reduced annual NH_3 emissions by 90% with respect to emissions found in the traditional anaerobic lagoon. Practical implication of this system needs further investigation as although it is effective, it is a costly option and would need further research to make it practical and affordable before establishing the technology at farm houses (Szogi et al., 2006). Melse and Timmerman, (2009) have reported the inclusion of a similar liquid treatment model that has resulted in failure because of increased cost of construction, labour, processing and maintenance resulting in business closure because of bankruptcy.

It is already known that ammonia emissions are highest immediately after application and most of the emissions occurred during the first 24 hours. Wulf et al., (2001) looked into the effect of digestion of slurry on trace gas emissions. Wulf et al., (2001) found that digestion of slurry (fermented) shows a positive overall effect in reducing trace gas emissions. The emissions of all monitored trace gases in this study except nitrous oxide were reduced compared to unfermented slurry. A non significant effect on nitrous oxide is not clear in this experiment. However, Wulf et al., (2001) concluded that spreading co-fermented slurry on grassland trail seems to be the most recommendable, especially if the effect of ammonia on eutrophication and acidification is considered (Wulf et al., 2001).

Microbial Activity methods

A microbiological review on pig odour by Zhu, (2000) discussed several odour control techniques that have been developed based on microbial activities and cited the limitations of the techniques. The odorous volatile fatty acids are mainly produced under anaerobic conditions with bacterial genera *Clostridium* and *Eubacterium* the major contributors. Pig manure contains sufficient nutrients for bacterial growth and the limiting factors that could affect the growth of these bacterial genera are most likely pH and temperature. *Clostridium* has the widest temperature range for growth among other bacterial genera. Zhu found that the available techniques for controlling odours are ineffective (microbial-based manure additives) or too costly (aeration). Raising manure pH can attenuate the growth of odour-causing bacteria, thus reducing odour emission but the adjustment of pH is only recommended for fresh manure as treating aged manure can release large quantities of either ammonia or hydrogen sulphide with potentially lethal effects.

Chapter 4 : Conclusion

A reduction in ammonia emissions is a European legal requirement and since odour from pig production facilities can pose a major nuisance in many rural areas, its reduction is also required to provide industry sustainability. The release of ammonia and odours into the environment can have a major impact over a wide area and negatively affect the quality of the environment both locally and nationally as well as the quality of rural life for locals and the enjoyment of the countryside for tourists. Research on ammonia and odour emissions at pig units is very technically challenging because the variations in concentrations and emissions of ammonia and odour compounds still cannot be fully explained and may be related to numerous factors.

With regard to odour, it was difficult for this review to make direct comparison due to the difference in measurement methodology. However the review suggests that although there were many volatile odour compounds (VOCs) identified, it was found that relatively few had the potency (a combination of concentration and low detection threshold) to become a problem odour. Most important nuisance VOCs were found to be sulphur compounds, especially hydrogen sulphide, p-cresol and other phenols, skatole and indole, ammonia and low molecular weight organic acids. Many of these compounds arise from the microbial activity of the gastrointestinal tract or microbial breakdown of the faeces, while ammonia arises from the breakdown of urine.
Whilst it is evident that further research is required to fully address the issue of 'effective ammonia and odour abatement methods', the review above has highlighted some opportunities. These include:

1) Dietary manipulation: reducing CP content of diets will reduce ammonia emissions. Furthermore, within a small window (between 18 and 15% CP) odour emissions may also be reduced although some studies would suggest that an increase in fermentable carbohydrate as well as a reduction in CP value has potential to have significant impacts on odour emissions.
2) Acid filtration of exhaust air is highly effective at reducing ammonia and odour emission but at a great cost.

3) Bio filtration of exhaust air is a lower cost method but is often not as effective as acid filtration of the air
4) Slat design has been found to reduce ammonia emissions and V shaped tank designs appear to be highly effective when reducing ammonia and odour emissions.
5) Removal of slurry is also successful although plain scrapper systems can sometimes not reduce ammonia effectively since this practice often spreads the faeces over surfaces
6) Some slurry additives and slurry coverings have been found to decrease ammonia and odour reductions

7) There is conflicting evidence with regard to floor design and bedding. In some circumstances part slatted flooring can increase ammonia and odour emissions due to soiling, although it does appear to reduce emissions if managed properly.

With regard to **cost effectiveness**, dietary manipulation will be the most cost effective with air filtration being extremely expensive to implement. Tank design and slurry management may also be cost effective depending on strategy adopted and individual farm circumstances for storage and future use of the slurry.

Chapter 5 Further research

The knowledge base concerning VOCs associated with pig rearing units has made considerable progress over the past number of decades. A large and increasing number of published reviews and research papers by institutions throughout the world has helped fellow researchers, producers and policy makers better understand the complex problems associated with investigations into VOC emissions from livestock facilities. However major gaps remain, none less than an updated inventory on ammonia emissions and the establishment of an odour inventory which would both help the initial 'national' measure of ammonia and odour emissions and the modelling of odour impact.

The literature review highlighted the high number of chemicals that are released from livestock facilities, but are all the odour compounds equally important? While most assessment methods consider the impact of odour compounds individually, it is likely that some low level chemicals could work together synergistically with others to heighten the odour released. Further work is required to establish whether the synergistic or cumulative effect of odour compounds plays a significant role.

From this study it would appear that the main malodour culprits released from pig rearing facilities are readily identifiable and appear to have a persistent presence in certain areas of the facilities. There is, however, a lack of information on the concentrations as well as the relative impact of these key odour compounds downwind from the piggery units. Future studies could be made to obtain these analyses along with available odour thresholds which would then enable an assessment of which odour compounds will have the most noxious impact at set distances downwind from the piggery.

Many of the odours making a key contribution to malodours from pig-houses are microbial in origin and relate to the microbiological activity within the gastrointestinal tract or in the faeces. The role of microorganisms in the gut has been a growing area of research in humans and it may be possible that the application of these findings and techniques to pigs may suggest answers to the malodours from pigs.

The study identified different techniques available for minimisation and abatement of odour emissions from pig production units and also highlighted that the problems of odour can be intrinsically linked to the problems of dust removal because VOCs can be fixed on to dust and some treatment methods are common to both pollutants. This would indicate that any abatement strategies that would control and reduce dust pollutants would also have a similar effect on VOCs.

A more detailed evaluation of the strengths and weaknesses of the latest techniques, as well as cumulative effects of these techniques (e.g. diet along with tank design) with respect to piggery units will be critically analysed in a separate systematic review. This will provide advice and set the guidelines to prioritise future research within a framework of a research program on the treatment of air emitted from piggery units.

References:

Aarnink, A., Swierstra, D., Van den Berg, A. and Speelman, L. (1997). Effect of type of slatted floor and degree of fouling of solid floor on ammonia emission rates from fattening piggeries. *Journal of Agricultural Engineering Research,* **66(2),** 93-102.

Aarnink, A.J.A. and Verstegen, M.W.A. (2007). Nutrition, key factor to reduce environmental load from pig production. *Livestock Science,* **109(1-3),** 194-203.

Aarnink, A.A.J., Roelofs, P.F.M.M., Ellen, H. and Gunnink, H. (1999). Dust sources in animal houses.ed^eds, *Proceedings of the International Symposium on Dust Control in Animal Production Facilities* Aarhus, Denmark. pp. 34-40.

Aarnink, A.J.A., Smits, M.C.J. and Vermeij, I. (2010). Reduction of ammonia emission from houses for growing-finishing pigs by combined measures. *Report 366. Wageningen UR Livestock Research, Lelystad, The Netherlands.*

Aarnink, A.J.A., van den Berg, A.J., Keen, A., Hoeksma, P. and Verstegen, M.W.A. (1996). Effect of slatted floor area on ammonia emission and on the excretory and lying behaviour of growing pigs. *Journal of Agricultural Engineering Research*, **64,** 299-310.

Amon, B., Kryvoruchko, V., Amon, T. and Zechmeister-Boltenstern, S. (2006). Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. *Agriculture, Ecosystems & Environment,* **112(2),** 153-162.

Amon, B., Kryvoruchko, V., Frohlich, M., Amon, T., Pollinger, A., Mosenbacher, I. and Hausleitner, A. (2007). Ammonia and greenhouse gas emissions from a straw flow system for fattening pigs: Housing and manure storage. *Livestock Science,* **112,** 199-207.

Bildsoe, P., Adamsen, A.P.S. and Feilberg, A. (2012). Effect of low-dose liquid ozonation on gaseous emissions from pig slurry. *Biosystems Engineering*, **113**, 86-93.

Blanes-Vidal, V., Hansen, M.N., Adamsen, A.P.S., Feilberg, A., Petersen, S.O. and Jensen, B.B. (2009a). Characterization of odor released during handling of swine slurry: Part I. Relationship between odorants and perceived odor concentrations. *Atmospheric Environment,* **43**, 2997-3005.

Blunden, J., Aneja, V.P. and Lonneman, W.A. (2005). Characterisation of non-methane volatile organic compounds at swine facilities in eastern North Carolina. *Atmospheric Environment*, **39**, 6707-6718.

Bottcher, R.W. (2001). An environmental nuisance: Odor concentrated and transported by dust. *Chemical Senses*, **26**, 327-331.

Bourdon, D., Dourmad, J.Y. and Henry, Y. (1997). Reduction of nitrogen output in growing pigs by multiphase feeding with decreased protein level. *48th Annual Meeting of the E.A.A.P*., 25th - 28th August 1997, Vienna.

Braam, C.R. and Swierstra, D. (1999). Volatilization of ammonia from dairy housing floors with different surface characteristics. *Journal of Agricultural Engineering Research*, **72,** 59-69.

Braam, C.R., Ketelaars, J. and Smits, M.C.J. (1997). Effects of floor design and floor cleaning on ammonia emission from cubicle houses for dairy cows. *Netherlands Journal of Agricultural Science*, **45,** 49-64.

Braude, R. (1980). Twenty five years of widespread use of copper as an additive to diets of growing pigs. In: P. L'Hermite and J. Dehandtschutter, Editors, Copper. *Animal Wastes and Sewage Sludge*, pp. 3-15.

Bruce, J.M. (1990). Straw-flow - A high welfare system for pigs. *Farm Building Progress,* **102,** 9-13.

Cabaraux, J.F., Philippe, F.X., Laitat, M., Canart, B., Vandenheede, M. and Nicks, B. (2009). Gaseous emissions from weaned pigs raised on different floor systems. *Agriculture Ecosystems & Environment,* **130,** 86-92.

Cambra-Lopez, M., Aarnink, A.J.A., Zhao, Y., Calvet, S. and Torres, A.G. (2010). Airborne particulate matter from livestock production systems: A review of an air pollution problem. *Environmental Pollution*, **158**, 1-17.

Canh, T.T., Aarnink, A.J.A., Mroz, Z., Jongbloed, A.W., Schrama, J.W. and Verstegen, M.W.A. (1998). Influence of electrolyte balance and acidifying calcium salts in the diet of growing-finishing pigs on urinary pH, slurry pH and ammonia volatilisation from slurry. *Livestock Production Science,* **56,** 1-13.

Carozzi, M., Ferrara, R.M., Rana, G. and Acutis, M. (2013). Evaluation of mitigation strategies to reduce ammonia losses from slurry fertilisation on arable lands. *Science of the Total Environment,* **449,** 126-133.

CEN. (2003). Air quality - Determination of odour concentration by dynamic olfactometry, EN13725. European Committee for Standardisation.ed^eds, Brussels, Belgium.

Chen, L., Hoff, S.J., Koziel, J.A., Cai, L., Zelle, B. and Sun, G. (2008). Performance evaluation of a wood-chip based biofilter using solid-phase microextraction and gas chromatography–mass spectroscopy–olfactometry. *Bioresource Technology,* **99(16),** 7767-7780.

Chmielowiec-Korzeniowska, A. (2009). The concentration of volatile organic compounds (VOCs) in pig farm air. *Annals of Agricultural and Environmental Medicine*, **16**, 249-256.

Colina, J., Lewis, A., Miller, P. and Fischer, R. (2001). Dietary manipulation to reduce aerial ammonia concentrations in nursery pig facilities. *Journal of Animal Science,* **79(12),** 3096-3103.

Cortus, E.L., Lemay, S.P., Barber, E.M., Hill, G.A. and Godbout, S. (2008). A dynamic model of ammonia emission from urine puddles. *Biosystems Engineering*, **99,** 390-402.

CVB (2000). Veevoedertabel. Centraal Veevoederbureau, Lelystad, The Netherlands.

Daumer, M., Guiziou, F. and Dourmad, J. (2007). Effect of dietary protein content and supplementation with benzoic acid and microbial phytase on the characteristics of the slurry produced by fattening pigs. *Journées de la Recherche Porcine,* **39,** 13-22.

de Lange, K., Nyachoti, M. and Birkett, S. (1999). Manipulation of diets to minimize the contribution to environmental pollution. *Advanced Pork Production,* **19,** 173-186.

Deshusses, M.A. and Gabriel, D. (2005). *Biotrickling filter technology.*, Verlag, Berlin, Heidelberg.: Springer.

Deshusses, M.A. (1997). Biological waste air treatment in biofilters. *Current Opinion in Biotechnology,* **8(3),** 335-339.

Devos, M., Patte, F., Rouault, J, Laffort, P. and Gemert, L.J. (1990). *Standardised Human Olfactory Thresholds.*, New York.: Oxford University Press.

De Vries, J.W., Aarnink, A.J.A., Koerkamp, P. and De Boer, I.J.M. (2013). Life Cycle Assessment of Segregating Fattening Pig Urine and Feces Compared to Conventional Liquid Manure Management. *Environmental Science & Technology,* **47(3),** 1589-1597.

Dewes, T. (1996). Effect of pH, temperature, amount of litter and storage density on ammonia emissions from stable manure. *Journal of Agricultural Science*, **127,** 501-509.

Doorn, M.R.J., Natschke, D.F., Thorneloe, S.A. and Southerland, J. (2002). Development of an emission factor for ammonia emissions from US swine farms based on field tests and application of a mass balance method. *Atmospheric Environment*, **36,** 5619-5625.

Dourmad, J.Y., Etienne, M., Valancogne, A., Dubois, S., Van Milgen, J. and Noblet, J. (2008). InraPorc: a model and decision support tool for the nutrition of sows. *Animal Feed Science and Technology,* **143,** 372-386.

Dourmad, J.Y., Guingand, N., Latimier, P. and Sève, B. (1999a). Nitrogen and phosphorus consumption, utilisation and losses in pig production: France. *Livestock Production Science,* **58,** 199-211.

Dourmad, J.Y., Henry, Y., Bourdon, D., Quiniou, N. and Guillou, D. (1993). Effect of growth potential and dietary protein input on growth performance, carcass characteristics and nitrogen output in growing-finishing pigs. In: Verstegen, M.W.A., den Hartog L.A., van Kempen, G.J.M., Metz, J.H.M. (Eds), Nitrogen flow in pig production and environmental consequences. EAAP Publication n°69, 206-211. Pudoc Scientific Publishers, Wageningen (NLD).

Dourmad, J.Y., Sève B., Latimier P., Boisen S., Fernandez J., Van de Peet-Schwering C. and Jongbloed A.W. (1999b). Nitrogen consumption, utilisation and losses in pig production in France, The Netherlands and Denmark. *Livestock Production Science,* **58,** 199-211.

Dourmad, J.Y., van Milgen, J., Brossard, L. and Noblet, J. (2012). Contribution of modeling to the optimization of nutrient supplies to reproductive sows. IPVS 10-13 June. Proceedings, Jeju, Korea, 51-62.

Driemer, J. and Van den Weghe, H. (1997). Nitrous oxide emissions during nitrification and denitrification of pig manure. In: Voermans, J.A.M., Monteny, G.J. (Eds.), Proceedings of the International Symposium on ammonia and odour control from animal production facilities. *Dutch Society of Agricultural Engineering, Wageningen*, The Netherlands, Vinkeloord, The Netherlands, pp. 389-396.

Elliot, H.A. and Collins, N.E. (1983). Chemical methods for controlling ammonia release from poultry manure. ASAE, paper 83-4521, p. 17.

El-Mashad, H.M., Zeeman, G., van Loon, W.K.P., Bot, G.P.A. and Lettinga, G. (2004). Effect of temperature and temperature fluctuation on thermophilic anaerobic digestion of cattle manure. *Bioresource Technology*, **95,** 191-201.

EPA. (2001). Odour Impacts and Odour Emission Control Measures for Intensive Agriculture (Final Report) ISBN 1-84095-84075-84097.

European Environment Agency (2010). European community emission inventory report 1990–2008 under the UNECE convention on long-range transboundary air pollution. *European Environment Agency,* Copenhagen, Denmark.

FAO (2006). Livestock's long shadow, environmental issues and options. FAO, Rome, Italy.

FAO (2011). World Livestock 2011 – Livestock in food security. FAO, Rome, Italy.

Feddes, J.J.R., Ouellette, C.A. and Leonard, J.J. (2000). A system for providing protein for pigs in intermediately sized grower/finisher barns. *Canadian Agricultural Engineering,* **42,** 209-213.

Garcia-Launay, F., van der Werf, H., Nguyen T.T.H., Le Tutour, L. and Dourmad, J.Y. (2013). L'incorporation d'acides aminés dans les aliments permet de réduire les impacts environnementaux de la production porcine. *Journées de la Recherche Porcine,* **45,** 123-128.

Garry, B., Fogarty, M., Curran, T., O'Connell, M. and O'Doherty, J. (2007). The effect of cereal type and enzyme addition on pig performance, intestinal microflora, and ammonia and odour emissions.

Gerdmann, M.M., Machmüller, A., Frossard, E. and Kreuzer, M. (1999). Effect of different pig feeding strategies on the nitrogen fertilizing value of slurry for *Lolium multiflorum*. *Journal of Plant Nutrition and Soil Science,* **162,** 401-408.

Gibbs, P., Parkinson, R., Misselbrook, T. and Burchett, S. (2002). Environmental impacts of cattle manure composting. In *Microbiology of Composting*, Springer, 445-456.

Gilhespy, S.L., Webb, J., Chadwick, D.R., Misselbrook, T.H., Kay, R., Camp, V., Retter, A.L. and Bason, A. (2009). Will additional straw bedding in buildings housing cattle and pigs reduce ammonia emissions? *Biosystems Engineering,* **102(2),** 180-189.

Godbout, S., Lemay, S.P., Marquis, A., Pouliot, F., Larouche, J.P., Hamel, D., Lachance, I., Belzile, M., Dufour, V. and Turgeon, N. (2006). Évaluation technico-économique d'un système de séparation liquide/solide des déjections à la source dans un bâtiment porcin et les impacts sur l'environnement. *Institut de Recherche et de Développement en Agro-environnement, Quebec, Canada*.

Granier, R., Guingand, N. and Massabie, P. (1996). Influence of hygrometry, temperature and air flow rate on the evolution of ammonia levels. *Journées de la Recherche Porcine*, **28,** 209-216.

Groenestein, C.M. (1994). Ammonia emission from pig houses after frequent removal of slurry with scrapers. *Proceedings of the XII World Congress on Agricultural Engineering*. CIGR, Merelbeke, Belgium, pp. 543-550.

Groenestein, C.M. and Van Faassen, H.G. (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, C.M., den Hartog, L.A. and Metz, J.H.M. (2006). Potential ammonia emissions from straw bedding, slurry pit and concrete floors in a group-housing system for sows. *Biosystems Engineering,* **95(2),** 235-243.

Groenestein, C.M., Monteny, G.J., Aarnink, A.J.A. and Metz, J.H.M. (2007). Effect of urinations on the ammonia emission from group-housing systems for sows with straw bedding: Model assessment. *Biosystems Engineering,* **97(1),** 89-98.

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,** 73-87.

Guarino, A., Fabbri, C., Brambilla, M., Valli, L. and Navarotto, P. (2006). Evaluation of simplified covering systems to reduce gaseous emissions from livestock manure storage. *Transactions of the Asabe,* **49(3),** 737-747.

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 pig. In: Proceedings of the international Symposium on Gaseous and Odour Emissions from Animal Production Facilities. *Danish Institute for Agricultural Sciences, Foulum, Denmark*, pp. 140-149.

Guingand, N. (2000). Preliminary results on the influence of emptying slurry pits on the emission of ammonia and odours from fattening buildings. *Journées de la Recherche Porcine,* **32,** 83-88.

Guingand, N. and Granier, R. (2001). The effects of partially or totally slatted floor during the growing/finishing period on the growth performance and ammonia emissions of pigs. *Journées de la Recherche Porcine*, **33,** 31-36.

Guingand, N., Demerson, L. and Broz, J. (2005). L'incidence de l'incorporation d'acide benzoïque dans l'alimentation des porcs charcutiers sur les performances zootechniques et l'émission d'ammoniac. *Journées de la Recherche Porcine,* **37,** 1-6.

Guiziou, F., Dourmad, J.Y., Saint-Cast, P., Picard, S. and Daumer, M.L. (2006). Reducing ammonia volatilisation from pig slurry through the reduction of dietary crude protein and the incorporation on benzoic acid. In: Petersen, S.O. (Ed), 12th Ramiran International Conference. Technology for recycling of manure and organic residues in a whole farm perspective, Vol I., 71-74.

Guo, H., Jacobson, L.D., Schmidt, D.R., Nicolai, R.E. and Janni, K.A. (2004). Comparison of five models for setback distance determination from livestock sites. *Canadian Biosystems Engineering,* **46**, 6.17-16.25.

Hacker, R.R., Ogilvie, J.R., Morrison, W.D. and Kains, F. (1994). Factors affecting excretory behavior of pigs. *Journal of Animal Science*, **72,** 1455-1460.

Hamelin, L., Godbout, S., Theriault, R. and Lemay, S.P. (2010). Evaluating ammonia emission potential from concrete slat designs for pig housing. *Biosystems Engineering,* **105(4),** 455-465.

Hamon, L., Andres, Y. and Dumont, E. (2012). Aerial Pollutants in Swine Buildings: A Review of Their Characterization and Methods to Reduce Them. *Environmental Science & Technology*, **46**, 12287-12301.

Hansen, M.N., Henriksen, K. and Sommer, S.G. (2006). Observations of production and emission of greenhouse gases and ammonia during storage of solids separated from pig slurry: Effects of covering. *Atmospheric Environment*. **40,** 4172-4181.

Hartung, J. (1985). Gas-Chromatographic Analysis of Volatile Fatty-Acids and Phenolic Indolic Compounds in Pig House Dust after Ethanolic Extraction. *Environmental Technology Letters,* **6**, 21-30.

Hassouna, M., Robin, P., Texier, C. and Ramonet, Y. (2005). NH_3, N_2O, CH_4 emissions from pig-on-litter systems. *Proceedings of the International Workshop on Green Pork Production, Paris, France*, pp. 121-122.

Hayes, E.T., Curran, T.P. and Dodd, V.A. (2006). Odour and ammonia emissions from intensive pig units in Ireland. *Bioresource Technology*, **97,** 940-948.

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

Hellmann, B., Zelles, L., Palojarvi, A. and Bai, Q.Y. (1997). Emission of climate-relevant trace gases and succession of microbial communities during open-window composting. *Applied and Environmental Microbiology*, **63,** 1011-1018.

Hobbs, P.J., Pain, B.F., Kay, R.M. and Lee, P.A. (1996). Reduction of odorous compounds in fresh pig slurry by dietary control of crude protein. *Journal of the Science of Food and Agriculture,* **71,** 508-514.

Hoff, S.J., Bundy, D.S. and Harmon, J.D. (2008). Modelling Receptor Odor Exposure from Swine Production Sources Using CAM. *American Society of Agricultural and Biological Engineers,* **24(6)**, 821-837.

Husted, S. (1994). Seasonal variation in methane emission from stored slurry and solid manures. *Journal of Environmental Quality*, **23,** 585–592.

INRA-AFZ (2004). Tables of composition and nutritional value of feed materials. In: D. Sauvant, J.M. Pérez and G. Tran (ed), 304 pp. *Institut National de la Recherche Agronomique, Association Française de Zootechnie, Paris, France*, 304 pp.

IPCC (2006). The international panel on climate change, Guidelines for National Greenhouse Gas Inventories: reference manual.

Jacobson, L.D., Guo, H., Schmidt, D.R., Nicolai, R.E., Zhu, J. and Janni, K.A. (2005). Development of the OFFSET Model for Determination of Odor-Annoyance-Free Setback Distances from Animal Production Sites: Part 1. Review and Experiment. *American Society of Agricultural Engineers,* **48(6)**, 2259-2268.

Jarret, G., Cerisuelo, A., Peu, P., Martinez, J. and Dourmad, J.Y. (2012). Impact of pig diets with different fibre contents on the composition of excreta and their gaseous emissions and anaerobic digestion. *Agriculture Ecosystems and Environment,* **45 (34),** 6204-6209.

Jarret, G., Martinez, J. and Dourmad, J.Y. (2011). Effect of biofuel co-products in pig diets on the excretory patterns of N and C and on the subsequent ammonia and methane emissions from pig effluent. *Animal*, **5 (4),** 622-631.

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

Johansen, K. and Poulsen, H.D. (2003). Substitution of inorganic phosphorus in pig diets by microbial phytase supplementation – a review. *Pig News and Information*, **24,** 77N -82N.

Jondreville, C. and Dourmad, J.Y. (2005). Le phosphore dans la nutrition des porcs. *INRA Production Animal,* **18,** 183-192.

Jondreville, C., Hayler, R. and Feuerstein, D. (2005). Replacement of zinc sulphate by microbial phytase for piglets fed a maize-soybean meal diet. *Animal Science*, **81,** 77-83.

Jondreville, C., Revy, P.S. and Dourmad, J.Y. (2003). Dietary means to better control the environmental impact of copper and zinc by pigs from weaning to slaughter. *Livestock Production Science,* **84,** 147-156.

Jondreville, C., Revy, P.S., Jaffrezic, A. and Dourmad J.Y. (2002). Le cuivre dans l'alimentation du porc : oligoélément essential, facteur de croissance et risque potentiel pour l'homme et l'environnement. *INRA Production Anima*l, **15,** 247-265.

Jongbloed A.W., Everts H., Kemme P.A. and Mroz, Z. (1999a). Quantification of absorbability and requirements of macroelements. In: I. Kyriazakis (eds), Quantitative biology of the pig, CAB International, Wallingford, UK, 275-298.

Jongbloed, A.W. and Lenis, N.P. (1992a). Alteration of nutrition as a means to reduce environmental pollution by pigs. *Livestock Production Science,* **31,** 75-94.

Jongbloed, A.W., Mroz, Z. and Kemme, P.A. (1992b). The effect of supplementary Aspergillus Niger phytase in diets for pigs on concentration and apparent digestibility of dry matter, total phosphorus, and phytic acid in different sections of the alimentary tract. *Journal of Animal Science,* **70,** 1159-1168.

Jongbloed, A.W., Poulsen, H.D., Dourmad, J.Y. and van der Peet-Schwering C.M.C. (1999b). Environmental and legislative aspects of pig production in The Netherlands, France and Denmark. *Livestock Production Science,* **58,** 243-249.

Kaiser, S. and van den Weghe, H. (1997). Regulatory control of nitrogen emissions in a modified deep litter system. In: Voermans, J.A.M., Monteny, G. (Eds.), Proceedings of the International Symposium : Ammonia and odour control from animal production facilities, Vinkeloord, The Netherlands, pp. 667-675.

Kaspers, B., Koger, J. and van Kempen, T. (2002). Evaluation of a conveyor belt waste collection system for swine: fecal drying efficiency and ammonia emission reductions. *Department of Animal Science North Carolina State University, Raleigh*.

Kim, K.Y., Jong Ko, H., Tae Kim, H., Shin Kim, Y., Man Roh, Y., Min Lee, C. and Nyon Kim, C. (2008). Quantification of ammonia and hydrogen sulfide emitted from pig buildings in Korea. *Journal of Environmental Management*, **88,** 195-202.

Kim, K.Y., Koh, H.J., Kim, H.T., Kim, Y.S., Roh, Y.M., Lee, C.M. and Kim, C.N. (2008). Odor reduction rate in the confinement pig building by spraying various additives. *Bioresource Technology*.

Knowlton, K.F., Radcliffe, J.S., Novak, C.L. and Emmerson, D.A. (2004). Animal management to reduce phosphorus losses to the environment. *Journal of Animal Science,* **82,** E173-E195.

Koger, J., Wossink, G., Kaspers, B. and van Kempen, T. (2002). Belt manure removal and gasification system to convert manure to fuel: the "RE-Cycle" system. *North Carolina State University.*

Kornegay, E.T. (2001). Digestion of phosphorus and other nutrients: the role of phytases and factors influencing their activity. In Enzymes in Farm Animal Nutrition, pp 237-271. M. R. Bedford and G. G. Partridge (Ed), CAB International, Wallingford, UK.

Koziel, J.A., Cai, L., Wright, D.W. and Hoff, S.J. (2006). Solid-Phase Microextraction as a Novel Air Sampling Technology for Improved, GC-Olfactometry-Based Assessment of Livestock Odors. *Journal of Chromatographic Science*, **44**, 451-457.

Kreuzer, M., Machmüller, A., Gerdemann, M.M., Hanneken, H. and Wittmann, M. (1998). Reduction of gaseous nitrogen loss from pig manure using feeds rich in easily-fermentable non-starch polysaccharides. *Animal Feed Science and Technology,* **73,** 1-19.

Kroodsma, W., Huis in't Veld, J. and Scholtens, R. (1993). Ammonia emission and its reduction from cubicle houses by flushing. *Livestock Production Science,* **35(3),** 293-302.

Kroodsma, W., Tveld, J. and Scholtens, R. (1993). Ammonia emission and its reduction from cubicle houses by flushing. *Livestock Production Science*, **35,** 293-302.

Krupa, S. (2003). Effects of atmospheric ammonia (NH< sub> 3</sub>) on terrestrial vegetation: a review. *Environmental Pollution,* **124(2),** 179-221.

Lachance, I. (2005). *Effets de la séparation des déjections porcines sous les planchers lattés sur les émissions gazeuses et d'odeurs*, unpublished thesis Université Laval.

Lagadec, S. (2012). Systèmes d'évacuations fréquentes des déjections. Rapport d'étude. *Chambres d'agriculture de Bretagne,* p. 10.

Latimier, P. and Dourmad, J.Y. (1993). Effect of three protein feeding strategies, for growing-finishing pigs, on growth performance and nitrogen output in the slurry and in the air. In: Nitrogen flow in pig production and environmental consequences. Pudoc Scientific Publishers, Wageningen, The Netherlands, pp. 242-245.

Latimier, P., Pointillard, A., Corlouër, A. and Lacroix, C. (1994). Influence de l'incorporation de phytase microbienne dans les aliments, sur les performances, la résistance osseuse et les rejets phosphorés chez le porc charcutier. *Journées de la Recherche Porcine*, **26,** 107-116.

Le, P.D., Aarnink, A.J., Ogink, N.W., Becker, P.M. and Verstegen, M.W. (2005). Odour from animal production facilities: its relationship to diet. *Nutrition Research Reviews,* **18(01),** 3-30.

Le, P.D., Aarnink, A.J.A. and Jongbloed, A.W. (2009). Odour and ammonia emission from pig manure as affected by dietary crude protein level. *Livestock Science,* **121(2-3),** 267-274.

Le, P.D., Aarnink, A.J.A., Jongbloed, A.W., van der Peet-Schwering, C.M.C., Ogink, N.W.M. and Verstegen, M.W.A. (2008). Interactive effects of dietary crude protein and fermentable carbohydrate levels on odour from pig manure. *Livestock Science,* **114(1),** 48-61.

Le, R.D., Aarnink, A.J.A., Jongbloed, A.W., Van der Peet-Schwering, C.M.C., Ogink, N.W.M. and Verstegen, M.W.A. (2007). Effects of dietary crude protein level on odour from pig manure. *Animal,* **1(5),** 734-744.

Le, P.H. (2006). *Odor from pig production: its relation to the diet.* Ph.D. thesis,

Leek, A.B.G., Callan, J.J., Reilly, P., Beattie, V.E. and O'Doherty, J.V. (2007). Apparent component digestibility and manure ammonia emission in finishing pigs fed diets based on barley, maize or wheat prepared without or with exogenous non-starch polysaccharide enzymes. *Animal Feed Science and Technology,* **135(1-2),** 86-99.

Lemay, S.P., Martel, M., Belzile, M., Zegan, D., Feddes, J., Godbout, S. and Pelletier, F. (2009). A systematic literature review to identify an air contaminant removal technology for swine barn exhaust air.ed^eds, *The Canadian Society for Bioengineering,* Prince Edward Island, Canada. pp. 13-30.

Lewis, E., Boyle, L., O'Doherty, J., Brophy, P. and Lynch, P.B. (2005). The effect of floor type in farrowing crates on piglet welfare.

Lim, T.T., Heber, A.J., Ni, J.Q., Kendall, D.C. and Richert, B.T. (2004). Effects of manure removal strategies on odor and gas emissions from swine finishing. *Transactions of the ASAE,* **47,** 2041-2050.

Mackie, R.I. (1994). Microbial production of odor components. in *International round table on swine odor control* ed.)^eds.), pp. 18-19, Ames, IA,USA.

Melse, R.W. and Moi, G. (2004). Odour and ammonia removal from pig house exhaust air using a biotrickling filter. *Water Science and Technology,* **50(4),** 275-282.

Melse, R.W. and Timmerman, M. (2009). Sustainable intensive livestock production demands manure and exhaust air treatment technologies. *Bioresource Technology,* **100(22),** 5506-5511.

Melse, R.W., Ogink, N.W. and Rulkens, W.H. (2009). Air treatment techniques for abatement of emissions from intensive livestock production. *The Open Agriculture Journal,* **3,** 6-12.

Milic, D., Tofant, A., Farkas, A. and Venglovsky, J. (2006). *Effect of natural zeolite, a slurry additive, on physicochemical slurry properties and aerial ammonia concentration in the pig farm nursery,* translated by 209-211.

Misselbrook, T.H. and Powell, J.M. (2005). Influence of bedding material on ammonia emissions from cattle excreta. *Journal of Dairy Science*, **88,** 4304-4312.

Misselbrook, T.H., Webb, J. and Gilhespy, S.L. (2006). Ammonia emissions from outdoor concrete yards used by livestock - quantification and mitigation. *Atmospheric Environment*, **40,** 6752-6763.

Mobley, H.L.T. and Hausinger, R.P. (1989). Microbial ureases - Significance, regulation, and molecular characterisation. *Microbiological Reviews*, **53,** 85-108.

Moeser, A.J., See, M.T., van Heugten, E., Morrow, W.E.M. and van Kempen, T.A.T.G. (2003). Diet and evaluators affect perception of swine waste odor: An educational demonstration. *Journal of Animal Science,* **81,** 3211-3215.

Monteny, G.J., Bannink, A. and Chadwick, D. (2006). Greenhouse gas abatement strategies for animal husbandry. *Agriculture Ecosystems & Environment*, **112,** 163-170.

Ni, J.Q., Heber, A.J., Darr, M.J., Lim, T.T., Diehl, C.A. and Bogan, B.W. (2009). Air Quality Monitoring and On-Site Computer System for Livestock and Poultry Environment Studies. *Transactions of the Asabe*. **52**, 937-947.

Ni, J.Q., Robarge, W.P., Xiao, C.H. and Heber, A.J. (2012). Volatile organic compounds at swine facilities: A critical review. *Chemosphere*, **89**, 769-788.

Ni, J.Q., Vinckier, C., Coenegrachts, J. and Hendriks, J. (1999). Effect of manure on ammonia emission from a fattening pig house with partly slatted floor. *Livestock Production Science*, **59,** 25-31.

Nicks, B., Laitat, M., Vandenheede, M., Desiron, A., Verhaeghe, C. and Canart, B. (2003). Emissions of ammonia, nitrous oxide, methane, carbon dioxide and water vapor in the raising of weaned pigs on straw-based and sawdust-based deep litters. *Animal Research*, **52,** 299-308.

Noblet J, Seve B and Jondreville C 2004. Nutritional value for pigs. In Tables of composition and nutritional value of feed materials: pigs, poultry, cattle, sheep, goats, rabbits, horses, fish (ed. D Sauvant, JM Perez and G Tran), pp. 25–35. *INRA Editions, Versailles, France*.

NRC (2012). Nutrient Requirements of Swine. Eleventh Revised Edition. National Academy Press, Washington, DC.

O'Neill, D.H. and Phillips, V.R.A. (1991). A review of the control of odour nuisance from livestock buildings: Part 1, The influence of the techniques for managing waste within the building. *Journal of Agricultural Engineering Research*, **50**, 1-10.

O'Neill, D.H. and Phillips, V.R.A. (1992). Review of the control of odour nuisance from livestock buildings: Part 3: Properties of the odorous substances which have been identified in livestock wastes or in the air around them. *Journal of Agricultural Engineering Research*, **53**, 23-50.

O'Shea, C., Sweeney, T., Lynch, M., Gahan, D., Callan, J. and O'Doherty, J. (2010). Effect of β-glucans contained in barley-and oat-based diets and exogenous enzyme supplementation on gastrointestinal fermentation of finisher pigs and subsequent manure odor and ammonia emissions. *Journal of Animal Science,* **88(4),** 1411-1420.

Oenema, O., Wrage, N., Velthof, G., Groenigen, J.W., Dolfing, J. and Kuikman, P. (2005). Trends in Global Nitrous Oxide Emissions from Animal Production Systems. *Nutrient Cycling in Agroecosystems*, **72,** 51-65.

Olivier, J.G.J., Bouwman, A.F., Van der Hoek, K.W. and Berdowski, J.J.M. (1998). Global air emission inventories for anthropogenic sources of NO_x, NH_3 and N_2O in 1990. *Environmental Pollution*, **102,** 135-148.

Osada, T., Rom, H.B. and Dahl, P. (1998). Continuous measurement of nitrous oxide and methane emission in pig units by infrared photoacoustic detection. *Transactions of the ASAE,* **41,** 1109-1114.

O'shea, C., Lynch, B., Lynch, M., Callan, J. and O'Doherty, J. (2009). Ammonia emissions and dry matter of separated pig manure fractions as affected by crude protein concentration and sugar beet pulp inclusion of finishing pig diets. *Agriculture, Ecosystems & Environment,* **131(3),** 154-160.

Otto, E.R., Yokoyama, M., Hengemuehle, S., von Bermuth, R.D., van Kempen, T. and Trottier, N.L. (2003). Ammonia, volatile fatty acids, phenolics, and odor offensiveness in manure from growing pigs fed diets reduced in protein concentration. *Journal of Animal Science,* **81(7),** 1754-1763.

Panetta, D., Powers, W.J., Xin, H., Kerr, B.J. and Stalder, K.J. (2006). Nitrogen excretion and ammonia emissions from pigs fed modified diets. *Journal of Environmental Quality,* **35(4),** 1297-1308.

Parker, D.B., Cai, L.S., Kim, K.H., Hales, K.E., Spiehs, M.J., Woodbury, B.L., Atkin, A.L., Nickerson, K.W. and Patefield, K.D. (2012). Reducing odorous VOC emissions from swine manure using soybean peroxidase and peroxides. *Bioresource Technology*. **124**, 95-104.

Parker, D.B., Koziel, J.A., Cai, L., Jacobson, L.D., Akdeniz, N., Bereznicki, S.D., Lim, T.T., Caraway, E.A., Zhang, S., Hoff, S.J., Heber, A.J., Heathcote, K.Y. and Hetchler, B.P. (2012). Odor and Odorous Chemical Emissions from Animal Buildings: Part 6. Odor Activity Value. *Transactions of the Asabe*. **55**, 2357-2368.

Pedersen, S. and Ravn, P. (2008). Characteristics of Floors for Pig Pens: Friction, shock absorption, ammonia emission and heat conduction. *Agricultural Engineering International: CIGR Journal*.

Pelletier, F., Marquis, A., Godbout, S., Joncas, R., Larouche, J., Massé, D. and Bégué, P. (2005). Gas and odor emissions from swine building materials. *Dimensions (mm),* **550(550),** 50.

Petersen, S.O. and Ambus, P. (2006). Methane oxidation in pig and cattle slurry storages, and effects of surface crust moisture and methane availability. *Nutrient Cycling in Agroecosystems*, **74,** 1-11.

Philippe, F.X., Cabaraux, J.F. and Nicks, B. (2011). Ammonia emissions from pig houses: Influencing factors and mitigation techniques. *Agriculture Ecosystems & Environment,* **141(3-4),** 245-260.

Philippe, F.X., Cabaraux, J.F., Laitat, M., Stilmant, D., Wavreille, J. and Nicks, B. (2012a). Les impacts environnementaux du choix des modalités d'hébergement des porcs charcutiers (rapport intermédiaire). *University of Liège, Liège, Belgium. Walloon Agricultural Research Centre, Gembloux, Belgium*.

Philippe, F.X., Cabaraux, J.F., Laitat, M., Vandenheede, M., Wavreille, J., Bartiaux-Thill, N. and Nicks, B. (2010a). Evaluation environnementale comparée de l'élevage de truies gestantes sur sols paillés et sur sols à caillebotis. *Project 2740/3. University of Liège, Liège, Belgium. Walloon Agricultural Research Centre, Gembloux, Belgium*.

Philippe, F.X., Canart, B., Laitat, M., Wavreille, J., Bartiaux-Thill, N., Nicks, B. and Cabaraux, J.F. (2010b). Effects of available surface on gaseous emissions from group-housed gestating sows kept on deep litter. *Animal*.

Philippe, F.X., Laitat, M., Canart, B., Vandenheede, M. and Nicks, B. (2007a). 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,** 144-152.

Philippe, F.X., Laitat, M., Canart, B., Vandenheede, M. and Nicks, B. (2007b). Gaseous emissions during the fattening of pigs kept either on fully slatted floors or on straw flow. *Animal*, **1,** 1515-1523.

Philippe, F.X., Laitat, M., Nicks, B. and Cabaraux, J.F. (2012). Ammonia and greenhouse gas emissions during the fattening of pigs kept on two types of straw floor. *Agriculture Ecosystems & Environment,* **150,** 45-53.

Philippe, F.X., Laitat, M., Vandenheede, M., Canart, B. and Nicks, B. (2006). Comparison of zootechnical performances and nitrogen contents of effluent for fattening pigs kept either on slatted floor or on straw-based deep litter. *Annales de Médecine Vétérinaire*, **150,** 137-144.

Philippe, F.X., Laitat, M., Wavreille, J., Bartiaux-Thill, N., Nicks, B. and Cabaraux, J.F. (2011). Ammonia and greenhouse gas emission from group-housed gestating sows depends on floor type. *Agriculture, Ecosystems & Environment,* **140,** 498-505.

Philippe, F.X., Remience, V., Dourmad, J.Y., Cabaraux, J.F., Vandenheede, M. and Nicks, B. (2008). Food fibers in gestating sows: effects on nutrition, behaviour, performances and waste in the environment. *INRA Productions Animales*, **21,** 277-290.

Pomar, C., Pomar, J., Babot, D. and Dubeau, F. (2007). Effet d'une alimentation multiphase quotidienne sur les performances zootechniques, la composition corporelle et les rejets d'azote et de phosphore du porc charcutier. *Journées de la Recherche Porcine,* **39,** 23-30.

Portejoie, S., Dourmad, J.Y., Martinez, J. and Lebreton, Y. (2004). Effect of lowering dietary crude protein on nitrogen excretion, manure composition and ammonia emission from fattening pigs. *Livestock Production Science,* **91(1-2),** 45-55.

Poth, M. and Focht, D.D. (1985). N-15 kinetic-analysis of N_2O production by nitrosomonas-europaea - An examination of nitrifier denitrification. *Applied and Environmental Microbiology*, **49,** 1134-1141.

Pouliot, F., Dufour, V., Godbout, S., Leclerc, B., Larose, L.A. and Trahan, M. (2006). Efficacy of a conveyor belt system to separate urine and feces beneath the slatted floor in gestation barns: mass balance and by-product characterization. *Journées de la Recherche Porcine*, **38,** 13-20.

Poulsen, H. D., Jongbloed, A.W., Latimier, P. and Fernandez, J.A. (1999). Phosphorus consumption, utilisation and losses in pig production in France, The Netherlands and Denmark. *Livestock Production Science,* **58,** 251-259.

Poulsen, H.D. (1995). Zinc oxide for weanling piglets. *Acta. Agric. Scand*. **59,** 159-167.

Poulsen, H.D. (2000). Phosphorus utilization and excretion in pig production. *Journal of Environmental Quality,* **29,** 24-27.

Powers, W.J. (1999). Odor control for livestock systems. *Journal of Animal Science,* **77,** 169-176.

Predicala, B., Cortus, E.L., Lemay, S.P. and Lague, C. (2007). Effectiveness of a Manure Scraper System for Reducing Concentrations of Hydrogen Sulfide and Ammonia in a Swine Grower-Finisher Room. *Trans. ASABE*, **50,** 999-1006.

Revy P.S., Jondreville C., Dourmad J.Y. and Nys Y. (2003). Le zinc dans l'alimentation du porc: oligoélément essentiel et risque potentiel pour l'environnement. *INRA Production Animal,* **16,** 3-18.

Revy, P.S., Jondreville, C., Dourmad, J.Y. and Nys, Y. (2005). Assessment of dietary zinc requirement of weaned piglets fed diets with or without microbial phytase. *Journal of Animal Physiology and Animal Nutrition,* **90,** 50-59.

Rigolot, C., Espagnol, S., Robin, P., Hassouna, M., Beline, F., Paillat, J.M. and Dourmad, J.Y. (2010). Modelling of manure production by pigs and NH3, N2O and CH4 emissions. Part II: effect of animal housing, manure storage and treatment practices. *Animal*, **4,** 1413-1424.

Ruth, J.H. (1986). Odor thresholds and irritation levels of several chemical substances: a review. *American Industrial Hygiene Association Journal*, **47**, A142-A151.

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

Sheridan, B.A., Hayes, T.P. and Dodd, V.A. (2004). A dispersion modelling approach to determining the odour impact of intensive pig production units in Ireland. *Bioresource Technology,* **91**, 145-152.

Smith, D.R., Moore, P.A., Haggard, B.E., Maxwell, C.V., Daniel, T.C., Van Devander, K. and Davis, M.E. (2004). Effect of aluminum chloride and dietary phytase on relative ammonia losses from swine manure. *Journal of Animal Science,* **82(2),** 605-611.

Sommer, S.G. (2001). Effect of composting on nutrient loss and nitrogen availability of cattle deep litter. *European Journal of Agronomy,* **14,** 123-133.

Sommer, S.G. and Moller, H.B. (2000). Emission of greenhouse gases during composting of deep litter from pig production - effect of straw content. *Journal of Agricultural Science*, **134,** 327-335.

Sommer, S.G., Petersen, S.O., Moller, H.B., 2004. Algorithms for calculating methane and nitrous oxide emissions from manure management. Nutrient Cycling in Agroecosystems 69, 143-154.

Sommer, S.G., Petersen, S.O., Sorensen, P., Poulsen, H.D. and Moller, H.B. (2007). Methane and carbon dioxide emissions and nitrogen turnover during liquid manure storage. *Nutrient Cycling in Agroecosystems*, **78,** 27-36.

Sommer, S.G., Zhang, G.Q., Bannink, A., Chadwick, D., Misselbrook, T., Harrison, R., Hutchings, N.J., Menzi, H., Monteny, G.J., Ni, J.Q., Oenema, O. and Webb,

J. (2006). Algorithms determining ammonia emission from buildings housing cattle and pigs and from manure stores. *Advances in Agronomy,* **Vol 89 89,** 261-335.

Sørensen, P. and Fernandez, J.A. (2003). Dietary effects on the composition of pig slurry and on the plant utilisation of pig slurry nitrogen. *Journal of Agricultural Science,* **140,** 343-355.

Spoelstra, S.F. (1980). Origin of Objectionable Odorous Components in Piggery Wastes and the Possibility of Applying Indicator Components for Studying Odor Development. *Agriculture and Environment*, **5**, 241-260

Sun, G., Guo, H.Q., Peterson, J., Predicala, B. and Lague, C. (2008). Diurnal Odor, Ammonia, Hydrogen Sulfide, and Carbon Dioxide Emission Profiles of Confined Swine Grower/Finisher Rooms. *Journal of the Air & Waste Management Association*, **58,** 1434-1448.

Svennerstedt, B. (1999). Drainage properties and ammonia emissions in slatted floor systems for animal buildings. *Journal of Agricultural Engineering Research,* **72(1),** 19-25.

Szogi, A.A., Vanotti, M.B. and Stansbery, A.E. (2006). Reduction of ammonia emissions from treated anaerobic swine lagoons. *Transactions of the Asabe,* **49(1),** 217-225.

Timmerman, M., Hoofs, A.I.J. ad van Wagenberg, A.V. (2003). Ammonia emission from four systems for group-housed sows. *Proceedings of the Swine Housing II conference. American Society of Agricultural and Biological Engineers, Saint Joseph, MI, USA*, pp. 122-128.

Trabue, S.L., Anhalt, J.C. and Zahn, J.A. (2006). Bias of Tedlar bags in the measurement of agricultural odorants. *Journal of Environmental Quality*, **35**, 1668-1677.

Trabue, S.K., Bearson, B. and Ziemer, C. (2011). Swine Odor Analyzed by Odor Panels and Chemical Techniques. *Journal of Environmental Quality*, **40**, 1510-1520.

Trabue, S., Scoggin, K., Mitloehner, F., Li, H., Burns, R. and Xin, H.W. (2008). Field sampling method for quantifying volatile sulfur compounds from animal feeding operations. *Atmospheric Environment,* **42**, 3332-3341.

van de Peet-Schwering C.M.C., Aarnink A.J.A., Rom H.B. and Dourmad J.Y. (1999). Ammonia emissions from pig houses in the Netherlands, Denmark and France. *Livestock Production Science,* **58,** 265-269.

van Kempen, T., Kaspers, B., Burnette, P., van Kempen, M. and Koger, J.B. (2003). Swine housing with a belt for separating urine and feces: key to flexibility? , *Proceedings of the Swine Housing II Conference. American Society of Agricultural Engineers, Saint Joseph, MI, USA*., pp. 159-165.

van Kempen, T.A.T.G. (2001). Dietary adipic acid reduces ammonia emission from swine excreta. *Journal of Animal Science,* **79,** 2412-2417.

van Milgen, J., Valancogne, A., Dubois, S., Dourmad, J.Y., Sève B. and Noblet, J. (2008). InraPorc: a model and decision support tool for the nutrition of growing pigs. *Animal Feed Science and Technology,* **143,** 387-405.

van Zeeland, A.J.A.M. and den Brok, G.M. (1998). Ammonia emission in a room for weaned piglets with a sloped pit wall. *Proefstation voor de Varkenshouderij, Rosmalen, The Netherlands*.

Van Gemert, L.J. and Nettenbreijer, A.H.E. (1977). Compilation of odour threshold values in air and water.ed^eds, *National Institute for Water Supply. and Central Institute for Nutrition and Food Research* Voorburg, The Netherlands. and Zeist, The Netherlands.

VanderZaag, A.C., Gordon, R.J., Glass, V.M. and Jamieson, R.C. (2008). Floating Covers to Reduce Gas Emissions from Liquid Manure Storages: A Review. *Applied Engineering in Agriculture*, **24**, 657-671.

Wright, D.W., Eaton, D.K., Nielsen, L.T., Kuhrt, F.W., Koziel, J.A., Spinhirne, J.P. and Parker, D.B. (2005). Multidimentional Gas Chromatography-Olfactometry for the Identification and Prioritization of Malodors from Confined Animal Feeding Operations. *Journal of Agricultural and Food Chemistry*, **53**, 8663-8672.

Wulf, S., Maeting, M., Bergmann, S. and Clemens, J. (2001). Simultaneous measurement of NH_3, N_2O and CH_4 to assess efficiency of trace gas emission abatement after slurry application. *Phyton-Annales Rei Botanicae,* **41(3),** 131-142.

Xing, Y., Guo, H., Feddes, J., Yu, Z., Shewchuck, S. and Predicala, B. (2007). Sensitivies of Four Air Dispersion Models to Climatic Parameters for Swine Odor Dispersion. *American Society of Agricultural and Biological Engineers,* **50(3)**, 1007-1017.

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

Yasuda, T., Kuroda, K., Fukumoto, Y., Hanajima, D. and Suzuki, K. (2009). Evaluation of full-scale biofilter with rockwool mixture treating ammonia gas from livestock manure composting. *Bioresource Technology,* **100(4),** 1568-1572.

Ye, Z., Li, B., Cheng, B., Chen, G., Zhang, G., Shi, Z., Wei, X. and Xi, L. (2007). A concrete slatted floor system for separation of faeces and urine in pig houses. *Biosystems Engineering,* **98(2),** 206-214.

Yin-Cheung, M.L., Koziel, J.A., Cai, L., Hoff, S.J., Jenks, W.S. and Xin, H.W. (2008). Simultaneous Chemical and Sensory Characterisation of Volatile Organic Compounds and Semi-Volatile Organic Compounds Emitted from Swine Manure using Solid Phase Microextraction and Multidimensional Gas Chromatography-Mass Spectrometry-Olfactometry. *Journal of Environmental Quality*, **37**, 521-534.

Zahn, J.A., Hatfield, J.L., Do, Y.S., DiSpirito, A.A., Laird, D.A. and Pfeiffer, R.L. (1997). Characterization of volatile organic emissions and wastes from a swine production facility. *Journal of Environmental Quality*, **26**, 1687-1696.

Zahn, J.A., DiSpirito, A.A., Do, Y.S., Brooks, B.E., Cooper, E.E. and Hatfield, J.L. (2001). Correlation of human olfactory responses to airborne concentrations of malodorous volatile organic compounds emitted from swine effluent. *Journal of Environmental Quality*, **30**, 624-634.

Zeeman, G. (1991). *Mesophilic and psychrophilic digestion of liquid manure.* PhD Thesis. Agricultural University, Wageningen, The Netherlands, p. 116.

Zhu, J. (2000). A review of microbiology in swine manure odor control. *Agriculture, Ecosystems and Environment,* **78**, 93-106.

Appendix

A summary list of volatile organic compounds (VOCs) and gases identified in pig production facilities.

COMPOUND	Air concentration [a] (mg m^{-3})	Odour detection threshold[b] (mg m^{-3})	Odour Activity Value[f] (OAV)	Odour descriptive	OAV Ranking[g]
(a) Acids					
Formic acid	✓	0.045[d] - 55.0[c]		Irritant, pungent	
Acetic acid	0.075-0.11	0.025[e]-0.363[c]	0.2-4.4	Irritant, pungent	
Propanoic acid	0.040-0.062	0.003[e]-0.110[c]	0.4-20.6	Irritant, pungent	12
Butanoic acid (Butyric acid)	0.0386-0.220	0.0004[e]-0.0145[c]	15.2-550	Irritant, rancid	5
2-Methylpropanoic acid (Isobutyric acid)	0.0084-0.015	0.005[e]-0.0724[c]	0.2-3	Irritant, pungent	
Pentanoic acid (Valeric acid)	0.0015-0.006	0.0008[e]-0.0204[c]	0.3-7.5	Irritant, unpleasant	18
2,2-Dimethylpropanoic acid	✓	-		Irritant	
3-Methylbutanoic acid (Isovaleric acid)	0.0141-0.064	0.0002[e]-0.0105[c]	6.1-320	Rancid, cheese	8
2-Methylbutanoic acid	0.013	0.00794[c]-0.02[e]	0.2-0.7	Irritant, stench	
Hexanoic acid	0.0015-1.095	0.02[e]-0.0603[c]	0.075-18.1	Irritant, sour cheese	14
4-Methylpentanoic acid	0.005-0.026	0.037[e]-0.0759	0.02-2.7	Irritant, pungent, cheese	
Heptanoic acid	0.005-0.051	0.022[e]-0.148[c]	0.23-2.32	Irritant, disagreeable, rancid	
Octanoic acid	✓	0.0003[e]-0.024[c]		Irritant, unpleasant, rancid	
Nonanoic acid	✓	0.0016[e]-0.0126[c]		Irritant	
Decanoic acid	✓	0.05[e]-0.0631[c]		Irritant	
Dodecanoic acid	✓	0.004[e]-0.0204[c]		Irritant	
Tetradecanoic acid	✓	-		Irritant	
Hexadecanoic acid	✓	-			
Benzoic acid	✓	-		Irritant	
Phenylacetic acid	✓	0.00003[e]-0.00724[c]		Irritant	
Hydrocinnamic acid	✓	-			

COMPOUND	Air concentration [a] (mg m^{-3})	Odour detection threshold[b] (mg m^{-3})	Odour Activity Value[f] (OAV)	Odour descriptive	OAV Ranking[g]
(b) Alcohols					
Methanol	✓	4.3[e]-186[c]		Alcoholic	
Ethanol	0.0037-0.015	0.64[e]-55[c]	0.00007-0.023	Irritant	
1-Propanol	0.018-0.06	0.075[e]-6.03[c]	0.003-0.8	Irritant	
2-Propanol	0.0015-0.087	3.9[e]-25.7[c]	0.0004-0.022	Irritant	
1-Butanol	0.0051	0.158[e]-1.51[c]	0.003-0.03	Irritant	
2-Butanol	0.00062	0.4[e]-5.25[c]	0.002	Irritant	
2-Methyl-1-propanol	✓	0.036[e]-2.57[c]		Irritant	
1-Pentanol	0.00073	0.4[e]-1.7[c]	0.002	Irritant	
3-Methylbutanol	✓	0.08[e]-0.162[c]		Pungent, repulsive,	
1-Hexanol	✓	0.04[e]-0.186[c]		Irritant	
1-Heptanol	✓	0.05[e]-0.120[c]		Irritant	
1-Octanol	✓	0.0316[c]		Irritant	
3-Octanol	0.00027	-		Irritant	
1-Decanol	✓	1.32[c]		Irritant	
1-Dodecanol	0.0007	0.1[c]	0.007	Irritant	
2-Methoxyethanol	✓	0.3[e]			
2-Ethoxy-1-propanol	✓	0.4[e]			
2,3-Butanediol	✓	-			
4-Methylcyclohexanol	✓	2350[d]		Irritant	
2-Phenylethanol	✓	0.00035[e]-0.0871[c]		Floral, rose	
2-Furanmethanol	0.0033	32.00[d]	0.001	Irritant	
(c) Aldehydes					
Formaldehyde	✓	0.033[e]-1.07[c]		Pungent, rotten cabbage	
Acetaldehyde	0.00734	0.0027[e]-0.339[c]	0.02-2.7	Pungent	
Propanal	✓	0.0225[d]		Irritant, suffocating odour	

2-Propenal (acrolein)	0.00023	0.069[e]-0.407[c]	0.003	Irritant	
Butanal	0.0003	0.00084[e]-0.0275[c]	0.01-0.36	Irritant	
COMPOUND	**Air concentration [a] (mg m^{-3})**	**Odour detection threshold[b] (mg m^{-3})**	**Odour Activity Value[f] (OAV)**	**Odour descriptive**	**OAV Ranking[g]**
2-Methylpropanal	0.003	0.015[e]-0.123[c]	0.02-0.2	Irritant, pungent	
2-Butenal	✓	0.389[c]-1.7[e]		Pungent, suffocating	
Pentanal	0.0014	0.0025[e]-0.009[e]	0.16-0.56	Irritant, stench	
3-Methylbutanal	0.00072	0.0016[e]-0.00813[c]	0.01	Stench, pungent	
2-Pentenal	✓	-		Irritant	
Hexanal	0.0021	0.0575[c]-0.067[e]	0.036	Irritant	
2-Hexenal	✓	0.034[e]-0.132[c]			
Heptanal	0.002	0.006[e]-0.0229[c]	0.33	Irritant, fruity, heavy	
Octanal	0.0021	0.0078[e]	0.27	Irritant	
Nonanal	0.0052	0.0003[e]-0.0135[c]	0.38-17.2	Irritant	15
2-Nonenal	✓	0.0005[e]-0.000871[c]		Irritant	
2,4-Nonadienal	✓	0.00025[c]			
Decanal	✓	0.00025[e]-0.00589[c]			
2,4-Decadienal	✓	0.00018[e]-0.000219[c]		Irritant	
2-Heptenal	✓	0.034-0.0631[c]			
Benzaldehyde	✓	0.0008[d]-0.186[e]			
Salicylaldehyde	0.0010	0.0380[c]	0.03	Irritant	
Furfural	✓	0.0240[d]-3.16[c]		Irritant	
(d) Amines					
Methylamine	✓	0.0012[e]-0.0246[c]		Irritant, putrid, fishy	
Ethylamine	✓	0.05[e]-0.603[c]		Irritant, ammoniacal	
n-Propylamine	✓	0.022[e]-0.0269[c]		Irritant	
i-Propylamine	✓	0.5[e]-0.676[c]		Irritant	
Pentylamine	✓	56.6[d]		Irritant	
Trimethylamine	0.00049-0.005	0.00026[e]-0.00589[c]	0.08-19.0	Irritant, fishy, pungent	13

Triethylamine	✓	0.33[e]-1.32[c]		Irritant, ammoniacal, fishy	
Anilene	✓	0.0002[d]-2.63[c]		Irritant	
Ammonia	0-18,	0.03[e]-4.07[c]	0-600	Sharp, pungent	4
COMPOUND	**Air concentration [a] (mg m^{-3})**	**Odour detection threshold[b] (mg m^{-3})**	**Odour Activity Value[f] (OAV)**	**Odour descriptive**	**OAV Ranking**
(e) Aromatics					
Benzene	0.00098	1.5[e]-12.0[c]	0.00008-0.00065	Irritant	
Toluene	0.0035-0.091	0.08[e]-5.89[c]	0.04-1.13	Irritant	
Xylene	✓	o.35[e]-3.8[c]			
Ethylbenzene	✓	0.0129[c]			
Methylstyrene	✓	0.759[c]			
Methylnaphthalene	✓	0.0581[d]		Irritant	
Naphthalene	✓	0.2[e] -1.5[d]			
(f) Esters					
Methyl formate	✓	165[e]-234[c]		Irritant	
Methyl acetate	✓	0.5[e]-19.1[c]		Irritant, pleasant	
Ethyl formate	✓	54[e]-57.5[c]			
Ethyl acetate	✓	0.6[e]-9.77[c]		Irritant, fruity	
Vinyl acetate	0.011	0.36[d]-2.19[c]	0.01-0.03	Sore, sharp	
Propyl acetate	✓	0.21[e]-2.45[c]		Irritant	
i-Propyl acetate	✓	1.9[e]-10.2[c]		Irritant	
Butyl acetate	✓	0.03[e]-0.933[c]		Irritant	
i-Butyl acetate	✓	1.7[e]-2.34[c]		Irritant	
Methyl salicylate	✓	0.275[c]		Irritant	
(g) Ethers					
Diethylether	✓	0.990[d]		Sweet, pungent, irritant	
2-Methylfuran	0.00014	90.45[d]	0.000015		
(h)Halogenated Hydrocarbons					
Chloroform	✓	3.0[e]-58.9[c]			

Dichloromethane	✓	100[c]		Irritant	
Trichloroethylene	0.032-0.0728	1.134[d]-26.9[c]	0.001-0.06	Irritant	
(i) Hydrocarbons					
n-Pentane	0.0027	6.6[d]-95.5[c]	0.00003-0.0004	Irritant	
COMPOUND	**Air concentration [a] (mg m^{-3})**	**Odour detection threshold[b] (mg m^{-3})**	**Odour Activity Value[f] (OAV)**	**Odour descriptive**	**OAV Ranking**
2-Methylpentane	0.0164	0.2886[d]	0.0568	Irritant	
n-Hexane	✓	79.4[c]		Irritant	
Cyclohexane	0.00014	1.435[d]-77.6[c]	0.000002-0.0001	Irritant	
n-Heptane	0.00042	40.7[c]	0.00001	Irritant	
(j) Ketones					
Acetone	0.00242	34.7[c]	0.00007	Irritant	
2,3-Butanedione	✓	0.000007[e]-0.0159[c]		butter-like	
2-Butanone	0.00090	0.7375[d]-23.4[c]	0.00004-0.0012	Irritant	
3-Hydroxy-2-butanone	✓	-		Irritant, butter-like	
3-Methyl-2-butanone	0.00014	16.2[c]	0.00001		
2-Pentanone	0.0036	5.5[c]	0.00065	Irritant	
3-Pentanone	✓	1.15[c]-3.0[e]		Irritant	
2,3-Pentanedione	0.00042	0.0214[c]	0.019	Irritant	
2-Octanone	✓	0.0912[c]		Apple	
2-Nonanone	0.00024	0.229[c]	0.001	Irritant	
2-Undecanone	0.00035	0.155[c]	0.00225		
Acetophenone	0.0005-0.019	0.01[e]-1.82[c]	0.05-1.9		
(k) Nitrogen heterocycles					
Indole	0.00049-0.005	0.0006[e]	0.8-8.3	Irritant, intense fecal odour,	16
3-Methylindole (skatole)	0.0017-0.044	0.00035[e]-0.00309[c]	14.2-125.7	Stench, intense faecal odour,	9
(l) Phenols					
Phenol	0.0078-0.033	0.022[e]-0.427[c]	0.355-1.5	Irritant	
4-Methylphenol (p-cresol)	0.041-0.26	0.00005[e]-0.00832[c]	4.93-5200	Irritant	2

3-Methylphenol	0.004	0.00022[e]-0.00355[c]	1.127-18.18	Irritant	
2-Methylphenol	✓	0.0004[e]-0.00776[c]		Irritant	
2-Methoxyphenol	0.00052	0.0037[e]-0.00525[c]	0.1	Irritant	
4-Ethylphenol	0.010-0.037	0.0035[e]-0.01[c]	0.57-112.8	Irritant	10
4-Methyl-2-nitrophenol	0.00013	0.135[c]		Irritant	
COMPOUND	**Air concentration [a] (mg m^{-3})**	**Odour detection threshold[b] (mg m^{-3})**	**Odour Activity Value[f] (OAV)**	**Odour descriptive**	**OAV Ranking[g]**
(m) Sulphur containing compounds					
Hydrogen sulphide	0.004-2.4	0.0001[e]-0.0257[c]	0.15-24000	Rotten eggs	1
Carbonyl sulphide	✓	0.05			
Dimethylsulphide	0.0005-1.528	0.0003[e]-0.00589[c]	0.09-509.3		6
Dimethyldisulphide	0.002-1.14	0.0011[e]-0.0479[c]	0.041-1036	Stench, putrid, disagreeable	3
Diethylsulphide	0.0035-0.011	0.0014-0.0145	0.24-7.86	Stench, putrid	17
Diethyldisulphide	✓	0.0003[e]-0.00219[c]		Stench, nauseating	
Dipropyldisulphide	0.01078	0.13[e]-0.447[c]	0.039-0.083	Stench, putrid	
Dimethyltrisulphide	0.002-0.574	0.0073[e]-0.00871[c]	0.229-78.6	Stench, putrid	11
Diphenylsulphide	0.0045	0.0026[e]-0.00776[c]	0.580-1.730	Stench, putrid	
Methyl mercaptan (Methanethiol)	0.108-0.813	0.00209[c]	51.7-389.0	Unpleasant	7
Ethyl mercaptan	✓	0.000043[e]-0.0759[c]		Rotten cabbage	
n-Propyl mercaptan	✓	0.0000032[d]-0.00282[c]		Stench, onion-like	
Allyl mercaptan	✓	0.000005[e]-0.00126[c]		Unpleasant stench	
n-Butyl mercaptan	✓	0.00537[c]		Unpleasant	
Thiophenol	✓	0.00014[e]-0.00145[c]		Rotten cabbage	
Benzyl mercaptan	✓	0.00813[c]		Stench, putrid, nauseating	

[a]Sources for findings of compounds in the atmosphere at pig rearing facilities include **O'Neill and Phillips (1992) (*2*)**; **Ni et al (2012) (*1*)**; **Parker et al 2012 (*14*)**; **Chmielowiec-Korzeniowska (2009) (*15*)**; **Blanes-Vidal et al (2009) (*11*)**. Compounds marked with ✓ refer to those identified but not quantified as reported by **Schiffman et al (2001(*3*)**.

[b]Odour detection thresholds are given in milligrams per cubic metre and reported values are from [c]**Devos et al (1990)(*16*)**, [d]**Ruth (1986) (*17*)** and [e]**Van Gemert et al (1977) (*18*)**. [f]Odour Activity Value (OAV) is defined as the concentration of a single chemical compound divided by the odour threshold for that compound. Those compounds with an OAV ≥ 1 are likely to contribute to the overall odour of an air sample, OAV study by [g]**Parker et al (2012) (*10*)**.