Revista Brasileira de Zootecnia
© 2008 Sociedade Brasileira de Zootecnia
ISSN impresso: 1516-3598
ISSN *on-line*: 1806-9290
www.sbz.org.br

R. Bras. Zootec., v.37, *suplemento especial* p.215-229, 2008

Environmental pollution control in pigs by using nutrition tools

Age W. Jongbloed

Division Animal Production, Animal Sciences Group of Wageningen UR, P.O. Box 65, 8200 AB Lelystad, The Netherlands

ABSTRACT - An experiment was conducted to evaluate the effect of different fluorine:phosphorus ratios in the diet on performance of broiler chickens. One thousand broiler chickens with one day old were allotted to a completely randomized experimental design with four treatments with five replications of fifty broilers per experimental unit. The treatments was composed by four phosphorus sources with fluorine: phosphorus ratios of 1:40, 1:60,1:80, 1:100 and fed during three experimental phases: 1-21, 22-42 and 43-49 days. In each phase, feed intake, weight gain and feed conversion were evaluated. At the end of experiment, two birds per replication were slaughtered and their tibias and samples of muscle tissue from breast were collec

Introduction

There is an increasing awareness of the impact of livestock production systems on the environment, especially in countries or regions with a dense animal population, e.g., in Denmark, The Netherlands or Brittany in France (Jongbloed et al., 1999). In the past, animals were fed home-grown feeds and the manure produced was regarded as a scarce and valuable commodity for maintaining soil fertility. This ensured nutrient recycling except for losses associated with storage, transport and nutrients deposited in milk, meat and eggs.

Livestock production per hectare has increased by using more nitrogen (N) and phosphorus (P) on dairy farming systems in the form of inorganic fertilisers and purchased feeds, or in pig and poultry farming by purchased feeds. Thus, crop production and animal production were specialised and separated, in many cases by large distances, like soybeans which are largely imported by The Netherlands from Brazil. As a consequence, large amounts of nutrients excreted in animal manure, are not fully utilized in the soil-plant-animal system and finally lost to the environment, resulting in accumulation.

Environmental concerns can be divided into three categories: concerns related to the soil (accumulation of nutrients), the water (eutrophication) and the air (global warming, ammonia, odours, dust). The major concern in many countries such as The Netherlands, is finding an acceptable balance between the input and output of N and minerals per hectare of cultivated land. A recent overview of heavy metal balances across EU member states (Eckel et al., 2005) shows that net accumulation rates for Cu vary from -138 to +908 g/ha/y (median value: 109 g/ha/y) and from -131 to +3523 g/ha/y (median: 389 g/ha/y) for Zn. The net positive input to soils inevitably will lead to an increase in the P, Cu and Zn level in the soil. This in turn leads to increased leaching rates or run-off from soil to ground- and surface waters. The continuation of the accumulation of minerals in soils from manure, therefore, will lead to even higher levels in surface waters. This can pose new restrictions on the use and disposal of manure or sludge (the latter is not relevant in the Netherlands since it is not allowed to be used). Furthermore, because of excessive application of manure and fertilisers per hectare of land, surplus precipitation and leaching, nitrate often exceeds tolerable values in fresh water as well as for P. Generally, the enrichment of the environment leads to less biodiversity. This aspect is stressed more and more in The Netherlands.

Ammonia and greenhouse gases, together with noxious odours from animal husbandry are also of concern. Animal husbandry causes 90% of the total NH_3 emission in The Netherlands (Anonymous, 2006). The contribution of agriculture in The Netherlands to emissions of CH_4 primarily from ruminants but also from storage of manure, and gases like N_2O which contribute to global warming (greenhouse effect) are 48% and 54%, respectively (Anonymous, 2006). Dust, noise, visual pollution, and animals and their manure as

---

Correspondências devem ser enviadas para: age.jongbloed@wur.nl

carriers of pathogens, may also be regarded as environmental concerns.

Protein (nitrogen/amino acids) and the minerals like P, Cu and Zn are essential dietary nutrients for maintenance and production of animals. However, to avoid unnecessary excretion of these nutrients, there should be a close balance between the animal's genetic potential and the quantity and quality of nutrients consumed (Jongbloed et al., 1999).

After having described the environmental concerns associated with intensive animal production with special reference to nitrogen, minerals such as P, Cu and Zn, and emissions of ammonia and bad smell, the aim of this paper is first to give some insight into the European and Dutch environmental legislation. Next, the national balance in The Netherlands is presented for N, P, Cu and Zn. Consequently, examples will be described on nutritional means to reduce the excretion of N, P, Cu and Zn, and reduction of NH_3 and odour. Only nutritional aspects will be discussed here, although the author is aware that aspects such as housing, mechanisation, labour and economy are also important.

Legislation

The legislative framework is continually evolving and developing at what seems an ever-increasing rate. On environmental side, the farmers must deal with the Nitrate Directive (EU, 1991), the Habitats Directive (1992), the Water Framework Directive (EC, 2000), Environmental Liability Directive (EC, 2004), the Integrated Pollution Prevention and Control (IPCC, 2005) Directive, the Waste Framework Directive (EC, 2006), Animal By-products Regulations (2002). Some of these Directives are incorporated into national legislations. More details on governmental policies and measures regulating nitrogen and phosphorus from animal manure in European agriculture has recently been described by Oenema (2004).

The most important ones will be briefly discussed. The Nitrate Directive of the EU (1991) for the protection of water is the first one. A maximal allowed level of 50 mg NO_3^-/L is given. For P a maximal level of 0.15 mg total P/L is allowed in The Netherlands. In 2000, the Water Framework Directive in the EU was established and will impose standards for "good quality" of surface waters (EC, 2000). In this Directive a framework is given which aims to maintain and improve the aquatic environment in the EU. As a result of this Directive, in The Netherlands, legislation was adopted regarding concentrations in soil and ground water for minerals (Staatscourant, 2004). In this document the target values for Zn in shallow and deep ground water are 65 and 24 μg solubilized Zn/L, respectively.

In 1999, the Gothenburg Protocol was adopted to abate acidification, eutrophication and ground-level ozone (Gothenburg, 1999). This protocol sets emission ceilings for 2010 for four pollutants: ammonia, sulphur, NO_x and VOC (Volatile Organic Compounds). These ceilings were negotiated on the basis of scientific assessments of pollution effects and abatement options. Countries whose emissions have a more severe environmental or health impact and whose emissions are relatively cheap to reduce, will have to make the biggest cuts. Once the Protocol is fully implemented, Europe's sulphur emissions should be cut by at least 63%, its NO_x emissions by 41%, its VOC emissions by 40% and its ammonia emissions by 17% compared to 1990. Table 1 shows an overview of emission ceilings for ammonia in some European countries and the EU. This table shows large differences in reduction of ammonia that should be achieved in 2010, and ranges from 43% for Denmark and The Netherlands to even an expansion of 10% for Portugal. For the EU as a whole 15% reduction of ammonia emission is foreseen. In 2008 negotiations have started to set new emission ceilings for the year 2020. The general opinion is that a further reduction will be enforced, especially in some countries.

Implementation of all these Directives and Regulations may e.g. lead to introduction of Water Protection Zones where certain farming activities may be restricted or even prohibited in order for water quality objectives to be met. In other areas where soil phosphate levels are above optimum as a consequence of repeated manure or slurry applications, future additions may be limited to no more than crop off-take.

In 2003, the EU adopted new maximum authorized levels of micro-minerals in animal rations, which for pigs are presented only for Cu and Zn (Table 2). The physiological requirements as mentioned in this document should be the basis for the maximum authorized dietary levels in the EU and not pharmacological doses such as those for Cu and Zn. One of the reasons was that Cu and Zn in animal manure can form a considerable environmental hazard now or in the future.

Table 1 - Emission ceilings for ammonia in some European countries (1000 tonnes per year; Gothenburg, 1999).

Country	Emission in 1990	Emission ceilings in 2010	Reduction% in 2010 (base year 1990)
Denmark	122	69	43
France	814	780	4
Germany	764	550	28
Ireland	126	116	8
Netherlands	226	128	43
Portugal	98	108	10% higher
Slovakia	62	39	37
United Kingdom	333	297	11
European Community	3671	3129	15

Table 2 - Overview of maximum allowed concentrations of Cu and Zn in diets for specific categories of pigs (mg/kg; EC, 2003).

	Copper (mg/kg) total diet		Zinc (mg/kg) total diet	
	EU till 2004	EU ≥2004	EU till 2004	EU ≥2004
	total	total	total	total
Piglets till 12 weeks of age	175	170	250	150
From 12 - 16 weeks of age	175	25	250	150
Fatteners from 16 weeks of age	35	25	250	150
Breeding sows	35	25	250	150

No legislation at EC level on odour emission has been set yet, but several member states have odour legislation such as Germany, Austria, Belgium and United Kingdom. In The Netherlands, revised legislation on odour emission has been implemented since 01-01-2007 (Staatscourant, 2006). The concentration of odour is expressed in European odour units per cubic meter air (ou$_E$/m^3), and is defined as the amount of odour-causing gases which, when diluted in 1 m^3 of air, can just be distinguished from clean air by 50% of the members of an odour panel. Odour emission is defined as the number of odour units emitted from a manure surface per second (ou$_E$/sec/m^2). In Staatscourant (2006), odour emission factors for various categories of animals and housing systems are listed, and expressed in (ou$_E$/sec/m^2). A growing-finishing pig from 25 kg to slaughter has an odour emission factor of 17.9, but with a chemical air washer in the building, this is 12.5 (30% reduction). The total emission from a farm is estimated by means of a dispersion model, and calculates the dispersion of odour between the emission point and the odour-sensitive object. According to the Dutch legislation, the maximal allowed odour load is 35 ou$_E$/m^3, but the authorities of the communities, who have to give permission for the livestock operation, may deviate from this.

Most farmers struggle to understand all of the legislation and its implications and their obligations whilst running a business with its everyday problems. It is important that they receive key facts and understand what they need to stay within the law. Some decide that there is an element of risk they are prepared to take as a part of running business, they may prioritise (Penlington, 2008).

Estimation of the load of nitrogen and minerals in The Netherlands

To give insight into the load of N and minerals per ha of land in The Netherlands, Table 3 lists the contributions of N and P from animal manure and fertilisers in The Netherlands together with the surplus of these minerals per ha of utilized agricultural area (CBS, 2002; LEI, 2005).

Table 3 demonstrates that an increase of N and P output from manure took place from 1970 to 1990 after which a substantial decrease was obtained (primarily as a result of legislation). Nevertheless, there is still a significant excess of N and P per ha of land.

Table 4 lists the contribution of several sources on the load of agricultural area in The Netherlands by Cu and Zn in 1980 and 2004 (g/ha of utilized agricultural area; Anonymous, 2006). It should be noted, however, that the input of Cu and Zn is underestimated because the use of minerals either supplied as a free premix or via drinking water is not taken into account.

Table 3. Amount of N and P in animal manure and fertilizers in The Netherlands (kg/ha utilized agricultural area; CBS, 2002; LEI, 2005).

	Nitrogen				Phosphorus			
Year	1970	1980	1990	2003	1970	1980	1990	2003
Manure	133	190	239	141	35	50	47	27
Fertilizer	185	240	201	122	22	17	16	10
Other	14	17	19	41	2	3	3	3
Total input	332	447	459	304	59	70	67	39
In crops	167	210	248	164	22	29	31	23
Surplus	165	237	211	140	37	41	36	16

Table 4. Load of Cu and Zn in utilised agricultural area in The Netherlands (g/ha).

	Copper		Zinc	
	1980	2004	1980	2004
Animal manure	525	208	900	600
Inorganic fertilizers	75	17	75	23
Wet and dry deposition	40	10	230	30
Other sources	60	10	85	80
Total input	680	245	1200	733
Output via crops	70	50	350	285
Net load, excl. leaching	610	195	850	448

Table 4 shows that compared to 1980, the input of Cu and Zn from manure has decreased substantially, mainly by setting lower maximum levels in the diets for pigs. However, animal manure is still the main contributor to the load of these minerals per ha of land. The net load of the minerals listed has more than halved since 1980, however, accumulation still occurs. Jongbloed and Kemme (2007) estimated the excretion and potential soil accumulation of Cu and Zn due to pig production only in the EU at several options. This was calculated on the basis of recent Eurostat data and performance characteristics of pigs in the countries of the EU, and if applicable, in several regions of these countries. Accumulation of Cu and Zn in the soil (20 cm deep) was expressed in the number of years that are necessary to obtain an increase of 1 mg/kg soil, in which leaching was not taken into account. It was shown that according to the current EU legislation (EC, 2003), it takes about 30 and 9 years for Cu and Zn, respectively, in the Netherlands, Belgium, Denmark and in the regions of Nordrhein-Westfalia (Germany), Brittany (France), Cataluna (Spain), Lombardia (Italy), Murcia (Spain), Niedersachsen (Germany) and Lisboa et Valo de Tejo (Portugal). The accumulation of Zn is more severe than that of Cu, even at maximal levels of 75 mg Zn/kg of diet it takes only 20 years for an enhancement of the Zn content in the soil of 1 mg/kg.

Based on proposed amounts of N and minerals that can be applied per ha of land (see Jongbloed and Kemme, 2007), Table 5 is presented showing how many growing-finishing pigs or breeding sows are allowed per hectare of land in The Netherlands. Concentrations of N and P in the diets are those currently used in practice in The Netherlands. Those for Cu and Zn are those according to EU legislation before and after 26th of January 2004 or at further reduced levels. Calculations for breeding sows include a sow and her piglets up to 26 kg.

Table 5. Number of growing-finishing pigs or sows allowed per hectare of land when complying proposed constraints in The Netherlands.

	N	P	Cu			Zn		
			EU< 2004	EU≥ 2004	15 mg/kg	EU< 2004	EU≥ 2004	80 mg/kg
Growing-finishing pigs (26-114 kg)	102	59	11	19	43	10	18	35
Breeding sows + piglets to 26 kg	12.6	5.9	0.9	1.0	5.0	1.2	2.0	3.8

Table 5 shows clearly that with regard to the number of growing-finishing pigs or sows allowed per ha of land, and with the current EU legislation, Cu and Zn are the most limiting minerals for applying manure and not N or P. Now only the manure of 19 growing-finishing pigs is allowed per ha of land to comply with the (proposed) Dutch legislation. The number of breeding sows allowed per ha of land is only one or two at the current EU and Dutch legislation. In some countries, 1500 to 3000 mg Zn/kg of feed is used because of its positive effect on health and performance of piglets. If only during 14 days post-weaning 3000 ppm of Zn is provided to the piglets, the excretion of Zn per sow per year is increased from 302 (EU≥ 2004) to 748 g.

Reduction of excretion of N, and emissions of ammonia and odour by altering nutrition

Numerous experiments have shown that a reduction in dietary protein and supplementation of diets with crystalline amino acids can have a profound impact on N excretion (Dourmad et al., 1999; Rademacher, 2000; Kerr et al., 2006). Lowering dietary crude protein level for growing-finishing pigs by 2%-units will reduce N excretion by approximately 20%. This is more than double the reduction observed for the first 1%-unit reduction in dietary protein because of changes from less digestible feedstuffs to better digestible ones (Lenis, 1989). The reduction of N excretion will not be further outlined here and the reader is referred to Jongbloed (2006).

Ammonia emission

Ammonia emission from pig manure originates mainly from urea in the urine. Nitrogen in the faeces comprises undigested dietary N and endogenous N, mainly as amino acids, and microbial N, partly present in nucleic acids. The main part of NH_3 emission from pig houses originates from manure storage and fouled floors (Aarnink, 1997). The urea concentration of urine and the pH of faeces and urine are important characteristics of excreta determining the rate of NH_3 emission (Van Vuuren and Jongbloed, 1994). The urea concentration is highly dependent on protein nutrition and can be altered by changing dietary protein content. Other relevant dietary factors are (fermentable) non-starch polysaccharides (NSP) and acidifying salts. Based on research at our institute during the last decade, the results of monofactorial effects of these factors and their combined effects on NH_3 emission were quantified both using an *in vitro* laboratory set up (Canh, 1998; Le, 2006) and occasionally as an *in vivo* experiment.

Several studies show that lowering dietary protein levels has a profound effect on NH_3 emission (e.g. Canh, 1998; Le, 2006; Cnockaert and Sonck, 2007; Powers et al., 2007). Figure 1 shows a much lower NH_3 emission at lowered protein contents. As a rule of thumb, each %-unit lower protein content reduces NH_3 emission by 10%. Lowered protein content, without compromising animal performance, can be achieved by supplementing crystalline amino acids although there are limits on supplementary levels.

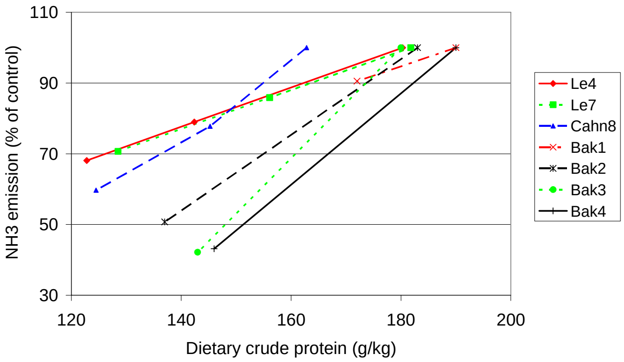

Figure 1. Relationship between dietary protein level and NH_3 emission (Le, 2006; Canh, 1998; Bakker et al., 2004; number after name in legend indicates chapter or treatment).

Non-starch polysaccharides are hardly digested in the small intestine but can be fermented by microbes in the large intestine of pigs. Microbes use NSP (as a source of energy) and undigested protein (as a protein source) to synthesize microbial mass. Surplus of undigested protein can be used as energy source as well. In that case protein is broken down and the released NH_3 is absorbed into the blood circulation and excreted as urea via urine. Thus, increased dietary fermentable NSP concentrations lead to a decreased ratio of urine-N and faecal-N (Figure 2 left; 8 experiments) and a reduced NH_3 emission (Figure 2 right; Jongbloed et al., 2007). In practical feeding of growing pigs, the problem is the lowered net energy content of most NSP-rich raw materials, resulting in lowered energy intake.

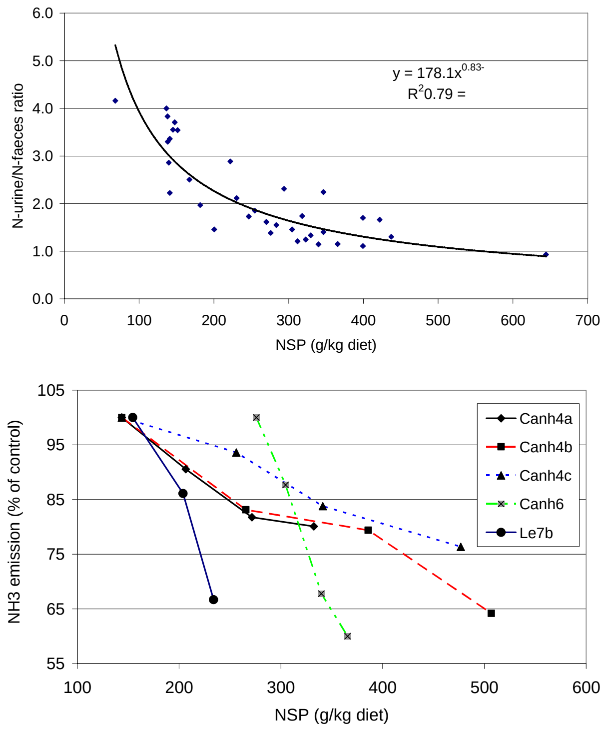

Figure 2 - Effect of NSP content on N-urine/N-faeces ratio (left) and on NH_3 emission (right)(Jongbloed et al., 2007).

The effect of acidifying salts was measured on urinary pH, nutrient retention and NH_3 emission from fouled floors and from the manure pit by growing pigs (Canh et al., 1998; Figure 3). The following treatments were used: $CaCO_3$, $CaSO_4$, Ca-Benzoate or $CaCl_2$ at two supplementation levels to obtain 7 and 10 g Ca/kg diet, except for $CaCO_3$, which was also used at 4 g Ca/kg. Diets with a high dietary electrolyte balance (dEB, meq/kg; $Na^+ + K^+ - Cl^-$) and with a low dEB were used. It was found that acidifying Ca-salts reduced urinary pH by 1.6 to 1.8 units, thereby diminishing NH_3 emission by 26 to 53%. Besides, reducing dEB from 320 to 100 meq/kg DM of diet lowered urinary pH by 0.48 units, and ammonia emission by 11%.

Finally, in a large scale balance experiment using a central composite design, 26 different diets were tested differing in levels of protein (142, 161 and 180 g/kg), $CaSO_4$ (added: 0, 9 and 18 g/kg), NSP (140, 210 and 280 g/kg) or fermentable NSP (60, 90 and 120 g/kg) to evaluate possible interactive effects of the dietary factors imposed on NH_3 emission (Bakker et al., 2004). Results showed that there was no interaction among the treatments. This means that the effects of described dietary factors on NH_3 emission are additive. Cumulative NH_3 emission could be estimated by the following equation

: NH_3 (g/7d) = -5.347 + 0.056 x protein – 0.050 x acidifying salt – 0.010 x NSP, $R^2 = 93.2$; protein, acidifying salt and NSP are in g/kg.

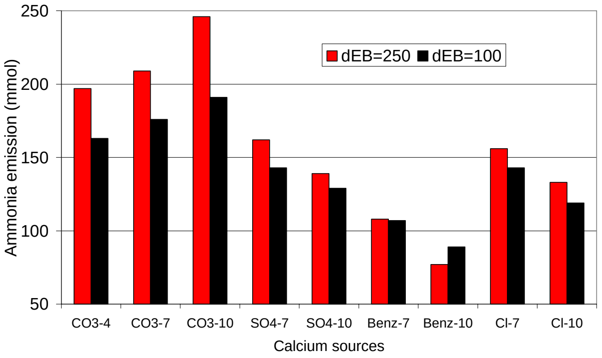

Figure 3 - Effect of acidifying salts on NH_3 emission (Canh et al., 1998).

From the experiments described above it was concluded that dietary factors imposed to reduce NH_3 emission from pig houses are additive within the ranges studied. The results of the *in vitro* model corroborated well with those of the *in vivo* studies.

In the Netherlands, so far the amount of NH_3 that is emitted has been related to total excretion of N. Therefore, we did a desk study to find out if there have been large changes in the portion of N that is excreted via faeces and urine, due to changes in N utilization and in diet formulation. Measurements on NH_3 emission were already carried out in 1991 and 1994 for growing-finishing pigs and breeding sows, respectively. The idea behind this study is that the emission mainly originates from urine N (ammoniacal N = TAN). The most prominent differences in the proportion of N excreted in urine were observed in breeding sows. Due to legislation on animal welfare in the EU, it is obligatory to feed diets to empty and pregnant sows with a high concentration of dietary fibre (minimal 140 g crude fibre/kg). The proportion of N in urine decreased from 72 to 63%, which has undoubtedly resulted in a lower amount of NH_3 emitted (Table 6). For growing-finishing pigs the proportion of TAN decreased from 72 to 67%.

© 2008 Sociedade Brasileira de Zootecnia

Table 6 - N balance of breeding sow and her piglets up to approx. 25 kg and of growing-finishing pigs in the nineties and in 2005 (kg/year).

	Breeding sow + piglets to 25 kg		Growing-finishing pigs from 26 to 116 kg	
	1994	2005	1991	2005
N in pig(let) diets (g/kg)	29.0	28.8	26.4	25.2
N in sow diets (g/kg)	25.4	23.1	-	-
N intake pig(let)s	18.09	19.87	19.66	18.98
N intake sows	27.40	26.42	-	-
Total N intake	45.49	46.30	19.66	18.98
N in excreta	31.38	29.77	13.70	11.91
N in faeces	8.80	11.10	3.84	3.98
N in urine	22.58	18.67	9.85	7.94
% N	71.9	62.7	71.9	66.6

Recently, there are strong indications that NH_3 is a precursor of particulate matter (Visser et al., 2001; Lester, 2007), and therefore, also reductions of NH_3 emission may become even more prominent.

Odour emission

Odour is a complex mixture of various volatile compounds, of which more than 300 may contribute to odour nuisance. Odorous compounds can be classified into four main groups: 1. sulphurous compounds, 2. indolic and phenolic compounds, 3. volatile fatty acids, and 4. ammonia and volatile amines (Le et al., 2005). Odour is emitted from animal houses, manure storage, and during field application of manure. It is mainly produced by the microbial conversion of feed components in the large intestine of pigs and after excretion by microbial conversion of excreta under anaerobic conditions in manure. In literature, most studies concerned reduction of dietary protein content on the concentrations of several odorous components in the manure (Hobbs et al., 1996; Sutton et al., 1999; Van Heughten and Van Kempen, 2002; Otto et al., 2003; Kerr et al., 2006). Several experiments were also carried out at our institute to investigate whether alteration of diet composition, and dietary protein content in particular, would reduce odour emission by pig production facilities (Le, 2006). In contrast to earlier studies in literature, all our measurements included olfactometry (with a sniffing panel) which were carried out according to the CEN standard 13725 (CEN, 2003). In the first experiment three diets were formulated with 120, 150 and 180 g protein/kg. In these diets barley was exchanged for extracted soybean meal. The most important results are presented in Table 7. Table 7 shows that at increasing dietary protein content, both odour concentration and odour emission were enhanced, especially when the protein content was increased from 150 to 180 g/kg. Also, the concentrations of several odorous compounds were increased at higher protein contents.

Table 7. Odour concentration and emission from manure and some manure characteristics of pigs fed different dietary protein levels (Le et al., 2007a)

Variables	Protein content in the diets (g/kg)		
	120	150	180
Odour concentration, ou_E/m^3	7259	13226	31888
Odour emission, $ou_E/s/m^2$	1.03	1.85	4.46
Total N, g/kg manure	5.78	6.24	7.25
pH	7.10	7.52	7.83
Phenol, mg/kg manure	9.1	17.3	32.7
Indole, mg/kg manure	6.0	9.8	10.0
Methylsulphide, mg/kg manure	1.4	8.1	6.5

In a second experiment, diets were formulated with high additions of crystalline amino acids to the diets. In one diet 10 g DL-methionine was added; methionine is the precursor of S-containing odorous compounds. In the other diet 1.4, 0.60 and 0.40 g/kg were added of L-tryptophan, L-phenylalanine and L-tyrosine, respectively, being precursors for the odorous compounds phenol, indole and 3-methyl indol (skatol). The most important results of this experiment are presented in Table 8.

Table 8. Odour concentration and emission from manure and some manure characteristics of pigs fed different types of amino acids (AA; Le et al., 2007b)

Variables	Diets		
	No addition of AA	Addition of 10 g Met./kg	Addition of Tryp., Phe. and Tyr.
Odour concentration, ou_E/m^3	13224	111302	16318
Odour emission, $ou_E/s/m^2$	1.88	15.48	2.23
Total N, g/kg manure	6.0	6.6	6.2
pH	7.75	7.65	7.93
Phenol, mg/kg manure	16.2	17.2	20.5
Indole, mg/kg manure	9.8	3.5	9.9
Methylsulphide, mg/kg manure	1.2	2.4	3.8

Table 8 shows that supplementation with DL-methionine, both odour concentration and odour emission were substantially enhanced, while by supplementation of L-tryptophan, L-phenylalanine and L-tyrosine these were not significantly enhanced. The concentrations of phenol and indole, however, were increased in the latter diets. The conclusion of this experiment is that dietary concentration of S has a large impact on odour emission by generation of e.g. hydrogen sulphide (H_2S). However, in contrast to what was expected, higher concentrations of phenolic and indolic compounds in the manure were not perceived by the odour panel as very offensive.

Other experiments by Le (2006) showed that several concentrations of fermentable protein (28 vs. 38 vs. 48 g/kg) did not show significant differences in odour concentration and odour emission among the treatments.

Using resistant potato starch in the diet (300 g/kg), Willig et al. (2005) observed substantial lower odorous components in the headspace of manure from growing pigs. This was also found in studies by Kerr et al. (2006), who used soybean hulls (150 to 170 g/kg) in their diets. In an other experiment, Le et al. (2008), however, showed a significant interaction between dietary protein content and the concentration of fermentable NSP on odour concentration and odour emission (Table 9).

Table 9. Odour concentration and emission from manure and some manure characteristics of pigs fed diets differing in content of protein and DNSP (fermentable NSP; 95, 145 and 195 g/kg, resp.; Le et al., 2008).

	Protein 120 g/kg			Protein 180 g/kg		
	Low DNSP	Medium DNSP	High DNSP	Low DNSP	Medium DNSP	High DNSP
Odour concentration, ou_E/m^3	4817	4964	9799	6124	4915	4146
Odour emission, $ou_E/s/m^2$	0.67	0.69	1.35	0.85	0.69	0.57
Total N, g/kg manure	5.2	5.6	5.8	8.1	8.0	9.2
pH	7.26	7.05	7.02	8.38	8.44	8.15
Phenol, mg/kg manure	56.0	53.5	50.6	107.7	100.9	135.9
Indole, mg/kg manure	7.3	8.5	8.5	13.3	10.2	15.2
Carbon disulphide, mg/kg manure	7.5	8.9	9.4	26.9	30.2	27.3

Surprisingly, it was shown for all experiments of Le (2006) that based on the olfactometry measurements, there was no correlation at all between odour emission and NH_3 emission.

Minerals

Phosphorus

It is important to supply dietary P in close accordance with the animals' requirement. This requires adequate knowledge about the digestibility (absorbability) of P in the feed used, and on the animal requirements for P. It has been recognised that the nutritional requirements for minerals in different countries may vary because of differences in housing conditions, genotype of the animals, level of feeding, major ingredients used in the diets and response criteria.

Results on apparent faecal P digestibility show that there are large differences among feedstuffs of plant origin. There are also substantial differences among those from animals and feed phosphates. The large variation in P digestibility among and within a feedstuff is attributed to differences in P and phytate P content, phytase activity and processing (Jongbloed and Kemme, 1990). Because feed phosphates are only used to supply P, one can easily choose those feed phosphates in which P is highly digestible. In the Netherlands, this has already led to an almost total shift to monocalcium phosphates (P digestibility = 83%) at the expense of dicalcium phosphates (P digestibility = 67%).

Raw materials with lowered concentrations of phytate P, such as low-phytate corn and soybean meal indeed show higher P digestibilities than the regular types of these seeds (Spencer et al., 2000; Bohlke et al., 2005; Dilger and Adeola, 2006).

The requirements for P are also expressed in terms of digestible P. Piglets and growing pigs deposit P in lean tissue, organs and bones and are estimated by the factorial approach. There is now a fairly good agreement of the requirement of P that is based on digestible P (Jongbloed et al., 2003; Jondreville and Dourmad, 2005). The amount of P deposited at a certain empty body weight is presented in Figure 4. When compared with data before 1985, there is no decline at higher body weights, as is indicated by the P retention per kg growth. This is possibly due to the higher lean production of the modern pigs. In this study it was also shown that modern growing-finishing pigs contain more phosphorus compared with pigs from experiments published before 1985 (Jongbloed et al., 2003).

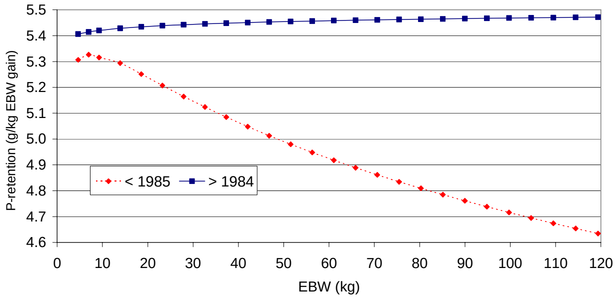

Figure 4 - Course of P retention in growing pigs in relation to empty body weight (EBW) and genotype (old - before 1985 and modern pigs - later than 1984; Jongbloed et al., 2003).

The requirements of pigs for Ca and digestible P are summarised in Table 10. The content of digestible P in terms of g/EW (1 EW equals 8.79 MJ NE or 12.55 MJ ME) decreases gradually from 2.4 at 25 kg live weight to 1.8 at 110 kg LW for a good type of gilt with a high feed intake capacity. It is obvious that the required amounts of digestible P are different at other growth rates. The recommended digestible P concentration for primiparous lactating sows is 2.7 g/EW having 10 to 11 piglets. If there are one or two piglets more per litter then the digestible P content should be increased by 0.3 and 0.4 g/EW, respectively.

Table 10 - Requirements of pigs for Ca and digestible P (g/12.55 MJ ME; Jongbloed et al., 2003)

Animal category	Calcium	Digestible P
Piglets		
0 to 2 weeks post-weaning	8.0	3.2
2 weeks post-weaning to 25 kg	9.5	3.4
Growing-finishing pigs		
25-35 kg	6.9	2.4
35-70 kg	6.4	2.2
>70 kg	5.7	1.9
Breeding sows		
< 70 days of pregnancy	5.0	1.5
70 – 98 days of pregnancy	6.6	2.0
>98 days of pregnancy	7.3	2.2
lactating	7.7	2.7

Phytase

Plant ingredients used to formulate pig diets may contain from 0.7 to 3.5% of phytates (Cosgrove, 1980). They are of very limited digestibility for pigs. Therefore, feed manufacturers and farmers have to add inorganic P from feed phosphates to their pig diets to cover the pig's P requirement. To enable dephosphorylation of the dietary phytates, intrinsic or extrinsic (microbial) phytases can be used. Since 1990, several experiments with exogenous microbial phytases were reported to quantify their effect on the apparent digestibility of P. A survey of a large part of these studies has been presented by Jongbloed et al. (2000). Numerous studies have been performed on evaluating efficacy of microbial phytase. Most studies show an exponential dose-response curve (Jongbloed et al., 2000; Jondreville and Dourmad, 2005; Kies et al., 2005). The latter authors showed that at 15,000 FTU/kg, an absorbability of P could be obtained of over 80% in starter pigs.

When 500 to 1000 units of Aspergillus niger phytase are added per kg of feed, the increase in amount of digestible P is equal to almost 50% of the requirement for digestible P of a growing pig. The efficacy of microbial phytase depends, apart from its origin, also on animal related factors like physiological status and housing conditions (Kemme et al., 1997a,b). It has also been demonstrated that microbial phytase is effective in breeding sows (Jongbloed et al., 2004a). With the high prices of feed phosphates there is a tendency to supplement more microbial phytase to the diets than one or two years ago.

In addition to the positive effect on the digestibility of P, microbial phytase also increases that one of the other mono- and divalent cations (Kies et al., 2006). Revy et al. (2004) showed that using 1200 U phytase (Natuphos®) in the basal diet largely exceeded the effect of adding 20 mg Zn/kg, while also Cu availability was increased from 9 to 18%. Revy et al. (2006) further stated that using 700 U phytase (Natuphos®) could replace even 35 mg Zn addition, but had no effect on Cu utilisation. Currently we carry out a meta-analysis on the relationship between the dose of microbial phytase and the Cu and Zn availability (Dijkstra et al., 2008).

Performance of pigs fed microbial phytase is better as compared with a non-supplemented diet or with a positive control diet (Jongbloed et al., 2000). The improvement in FCR can be attributed to increased digestibility of protein/amino acids and a slight increase in energy digestibility. The magnitute of the effect also depends on the dietary phytate content.

Phytase-supplemented feeds for growing-finishing pigs and pregnant sows may need little or no supplementary feed phosphate, thereby reducing total dietary P content and excretion of P. Microbial phytase has been incorporated in more than 80% of pig feeds in The Netherlands.

The environmental impact of microbial phytase is substantial. It is generally accepted that by using 500 FTU/kg of feed, about 0.8 g digestible P/kg is generated which is equivalent to 1.0 g P from monocalcium phosphate or to 1.23 g P from dicalcium phosphate.

Novoselova (2007) studied the implications of using modern technologies like GMO phytase, Enviropig and low-phytate cereals in pig production in The Netherlands. Using a diet commonly used in West-Europe and a typically maize-soybean meal diet used in the USA, the following input-output balance for P was estimated (Table 11).

Table 11 - Intake and excretion of P of a pig from 25 to 115 kg receiving West-European diets (WE) and a maize-soybean meal (CSBM) diet at different options (g/pig; Novoselova, 2007).

	P supplemented		Total P intake		P excretion	
	CSBM	WE	CSBM	WE	CSBM	WE
Standard with MCP	389	262	1137	1313	660	840
Microbial phytase	178	37	927	1089	450	620
Enviropig	0	0	403	1051	300	580
Low-phytate	139	209	887	1270	410	800

Table 10 shows that for West-European diets, the excretion of P with the standard and low-phytate diets hardly differed. This is due to the fact that the inclusion level of low-phytate soybean meal in West-European diets is rather low and also hardly low-phytate-corn is used in these diets. The differences with a typical corn-soybean meal diet are indeed substantial lower compared to the standard diet. The excretion of P using microbial phytase and with the Enviropig are also small, because West-European diets are rather high in total P content. In this way despite of the higher digestibility of the diet with the Enviropig, no great advantage over microbial phytase can be obtained, but with corn-soybean meal diets the P excretion is much lower.

Copper and zinc

Nutritional requirements for Cu and Zn are to a large extent based on research at lower animal production levels than those of modern genotypes. Maybe, like for P, modern pigs have a higher requirement for Cu and Zn than previous genotypes. Therefore, to get a better insight into the actual nutritional requirements, we critically evaluated the background of the recommendations for pigs (Jongbloed et al., 2004b). In various cases, information is lacking as to whether recommendations are “true” minimum requirements or include a safety margin. Judgement of the recommendations is, therefore, difficult. The Cu and Zn needs may depend on the nature of the diet (other compounds interfering with absorption and utilisation of Cu or Zn), but this is difficult to quantify. We also discriminated diets into (semi)synthetic, maize-soybean meal diets and other types of diets.

Table 11 summarizes the recommendations on requirements of Cu and Zn in different countries for specific categories of pigs and those obtained in our study. In some countries no discrimination is given between requirements according to category of the animal. This means e.g. that the same requirement is given for growing and lactating animals, which is indicated in Table 12.

Table 12 - Summarised inventory of requirements of Cu and Zn for piglets and growing-finishing pigs in different countries and the results of our study (concentrations as mg/kg fresh diet; Jongbloed et al., 2004b revised).

Piglets and growing-finishing pigs				
	Requirement of Cu		Requirement of Zn	
Country		Our study		Our study
BSAS, 2003 (UK)	6 (added) for piglets	4 added to a diet	100 (added) for piglets	67
	6 (added) for G-F pigs		60 – 100 (added) for G-F pigs	
NRC, 1998 (USA)	5 – 6 for piglets		80 – 100 for piglets	
	3 – 4 for G-F pigs		50 – 60 for G-F pigs	
GfE, 2008 (D)	5 -6 for piglets		70 – 88 for piglets	
	4 - 5 for G-F pigs		44 – 53 for G-F pigs	
INRA, 1989 (F)	10*		100*	

• = same for all categories of the specific animal species

© 2008 Sociedade Brasileira de Zootecnia

Table 12 shows that the recommended requirements vary substantially among the different countries. The recommendations of Cu for growing-finishing pigs are in rather good agreement with our results. An addition of 4 mg/kg Cu to a complete diet (88% DM) seems to be sufficient. The recommendations for Zn in different countries for growing-finishing pigs are intermediate with our results. Based on maize-soybean meal diets we concluded that 57 mg Zn/kg seems to be sufficient. However, a concentration of 67 mg Zn/kg is recommended for pigs receiving other diets than maize-soybean meal. Recommendations for Cu and Zn were assessed in diets without microbial phytase. Based on results describing enhanced Zn availability by using microbial phytase, this should offer possibilities to take this in account when formulating diets for pigs. No definitive answer could be obtained if and how much the requirements should be enhanced at higher animal performance levels than documented in the literature. No large differences were noted between various inorganic Cu sources for pigs, except for CuO and CuS, which are least available (Jongbloed and Kemme, 2007). Zinc sulphate shows a slightly higher availability than ZnO. It is surprising that the mineral chelates in the study of Jongbloed et al. (2004b) did not show higher availabilities than the inorganic Cu and Zn sources. However, they reviewed literature until 2002. Maybe, newer types of organic minerals show a more convincing positive effect on availability. Some unpublished data look promising.

It may be discussed on what essential levels of both metals in feed additives should be in view of environmental effects on soils and ecosystems. At present, there is a substantial gap between what is believed to be required by the animal versus what is allowed according to EU regulations; most of the feed compounders seem to utilise the maximal allowed quantities in the diets.

Other aspects

For N and P, the concentration of digestible amino acids and P per kilogram feed can decrease as the live weight of the pig increases from 25 to 115 kg. Therefore, the introduction of a two-, three- or multi-phase feeding system will help balance digestible nutrients in the diet to the requirements of the animals. Phase-feeding leads to less N and P excretion: in the case of one additional feed up to 6% according to Lenis (1989). A slightly larger reduction in P excretion by growing pigs can be achieved by mixing a feed rich in protein and minerals (feed A) with a feed having a low concentration of protein and minerals (feed B) in a changing ratio during the fattening period (multi-phase feeding). This mixing system can be achieved with a computerised mechanical feeding system.

Required concentrations of digestible amino acids and P per kg feed for breeding sows are much lower during pregnancy than during lactation. The use of separate diets for pregnancy and lactation compared with one diet for both reduced the excretion of P by 20% (Everts and Dekker, 1994).

A powerful tool to decrease the excretion of N and P is to aim at improvement of the feed conversion ratio of pigs. One and the same diet is offered to pigs that have large differences in their potential for growth, and consequently in their feed conversion ratio. This means also a large range in utilisation and thus excretion of N, P, Cu and Zn by a growing-finishing pig. Table 13 shows the effect of different feed conversion ratios (average, best and worst 20% of the farms in The Netherlands in 2006) on the excretion of P and Zn by a growing-finishing pig from 25 to 110 kg LW. A feed conversion ratio that is obtained on the worst 20% of the pig farms as compared with the best 20%, results in 0.19 kg more P and 6 g Zn excreted per pig. Thus, by improved performance (genetical improvement of pigs) reduction of the excretion of minerals can be achieved.

Table 13 - Effect of different feed conversion ratios on P and Zn excretion (kg/pig) by growing-finishing pigs (25-110 kg).

Feed conversion ratio	FCR average of farms; 2.69		FCR worst 20% of farms; 2.93		FCR best 20% of farms; 2.46	
	P	Zn	P	Zn	P	Zn
Intake (kg)	1.12	0.034	1.22	0.037	1.02	0.031
Excretion (kg)	0.66	0.033	0.76	0.036	0.57	0.030
Excretion (relative to average = 100)	100	100	115	109	86	91

Course of P and Cu excretion by growing-finishing pigs in The Netherlands

Table 14 summarises the course of P and Cu excretion by growing-finishing pigs in practice in The

Netherlands. From 1973 to 2006 the total P content in diets for growing-finishing pigs has decreased by more than 2.5 g/kg. Meanwhile, the feed conversion ratio has improved substantially, while the health of the pigs has not been compromised. The decrease in P excretion from 1991 to 2000 is predominantly the phytase effect. Phosphorus excretion in the period 1973 to 2006 decreased by 1.00 kg per pig, which is almost two-thirds! With regard to Cu excretion a significant decrease can be noted: in 2006 only 10% of the amount excreted in 1973. This is mainly due to legislation on maximal allowed concentrations in pig diets.

Table 14 - Mean excretion of P and Cu of growing-finishing pigs from 25 to 110 kg in The Netherlands (kg or g/pig)

Year	In diet (g/kg)	In diet (mg/kg)	Feed conversion ratio	Excretion (kg)	Excretion (g)
	P	Cu		P	Cu
1973	7.4	250	3.37	1.66	71
1983	6.2	175/125	3.08	1.18	33
1988	6.0/5.0[a]	175/35	2.96	0.89	16
1992	5.5/4.9	175/35	2.87	0.76	14
1996	5.3/4.6	175/35	2.71	0.64	14
2001	5.3/4.6	175/35	2.57	0.57	12
2006	5.4/4.8	170/25	2.69	0.66	8

[a] 6.0/5.0 means 6.0 g/kg in the starter diet and 5.0 g/kg in the grower-finisher diet

Discussion and applications for practice

At the interface of sustainable agriculture and pig production, Honeyman (1996) indicates four levels of issues: specifically the farm, the rural community, the society or consuming public, and the ecosystem or environment. It could be speculated that in the future pig production will have to deal with more constraints that are imposed from society, more than in the past. This may relate to animal well-being and health, quality of the animal product and production system, utilisation of nutrients, and last but not least from an environmental viewpoint.

First of all, it should be noted that animal manure still contains valuable plant nutrients in abundance, producers need to work closely with those utilising these so that effective recovery can take place. Better utilisation of nutrients by plants is highly desirable. Recent rises in fertiliser prices has renewed interest in organic manures, especially among arable farmers. This offers new interest in pig manure and undiluted slurry.

Another aspect is that there is a recognised time lag between the current action plans to control emissions of nitrates, minerals and gases coming into force and improvements in soil, water and aerial quality.

Application of nutrients via manure and/or chemical fertilisers on the fields should be in close balance with the uptake by the crop, with minor losses via leaching or to prevent gaseous emissions of ammonia, odour and nitrous oxide. This is part of our goal to achieve a sustainable agriculture. The problem is when there is an imbalance in the supply of, and the demand for certain nutrients, not only for crops but also in relation to livestock production. Manure legislation can help to achieve a better balance in nutrient input and output. Also, a regional approach can be recommended. Furthermore, farmers will be forced more to apply Best Available Techniques (BAT) to further reduce emissions. This may include greater attention to the design of housing. The adoption of BAT is defined in the EC BAT Reference document for intensive agriculture (BREF, 2006). This includes: management of housing and facilities, staff training, records, emergency procedures, repair and maintenance procedures, planning of activities on site, feeding and application of manure to land.

Nutrition management can substantially contribute to reductions in N, P, Cu and Zn excretion by pigs, and ammonia and odour emissions. Adequate knowledge is required on the digestibility of amino acids and P in the feed used, but for Cu and Zn no adequate data are available yet. New technologies are required to increase the digestibility of Cu and Zn substantially. Supplementary microbial phytase can enhance the digestibility of P by 20% or more so that feeds for growing-finishing pigs and for pregnant sows may need little or no supplementary feed phosphate. Phosphorus excretion can be lowered by 20 to 30% by using microbial phytase. Also, digestibility of at least Zn is increased by microbial phytase. More powerful microbial phytases are necessary to further hydrolyse phytate, and so to enhance digestibility of P. A favourable feed conversion ratio also contributes to a lower excretion of minerals per pig.

It is known that ruminants and pigs consume a lot of by- or co-products and also (moist) co-products. These co-products may originate from several food-processing industries, etc. In this respect, pigs are used to utilise products that are not or can not be used for modern human consumption, as has been the case in past centuries (De Boer, 1980). Therefore, pigs substantially contribute in reducing industrial wastes. Because part of these products has a lower digestibility and utilisation of N and P compared with common feedstuffs, they seem to become less attractive for the farmer to obtain a better balance of nutrients at farm level. As a consequence, part of these waste products may be transported directly to the refuse dump, which is even worse. Apart from the higher costs for the producer of these waste products, and possibly the higher price for the food to be paid by the consumer, this should worsen the national or regional mineral balance. Home-grown feeds can also contribute to a better regional mineral balance.

Current knowledge concerning the possible reduction of the manure surplus has to be integrated into future feed strategies. A further integration of the nutrition research with other disciplines is necessary. In this respect, both the genetic potential of the animals and hygienic conditions should be evaluated. An approach more at system level should be emphasised.

Conclusions

Soil fertility and quality of the surface and groundwaters and the air determine to a large extent the amount of manure that can be applied per hectare. Nowadays, on most intensive livestock farms the input of N, P, Cu and Zn by means of feeds and inorganic fertilizers often exceeds the output in meat, milk or eggs. Therefore, new legislations have been enforced, that limit the use of animal manure per hectare of land or put limits on maximal allowed contents of minerals in diets. However, animal manure is still a valuable commodity to maintain or improve soil fertility.

Accumulation in the soil is more severe for Zn than for Cu in the EU, but it is more a regional than a countrywide problem. Alleviation of this accumulation is only possible when growth-promoting levels in pig diets are banned, and Cu and Zn sources enter the market which are much more absorbable.

Nutrition management can substantially contribute to reduction in N and P excretion. Adequate knowledge is required on the availability/digestibility of P in the feeds used and on the requirement of P at any stage and type of production. The digestibility of P can be enhanced by using microbial phytase, resulting in a lowered P excretion of 20 to 30%. Also the availability of Zn is increased by microbial phytase. In the future more tailored nutrition and feeding strategies will be applied to obtain a further reduction of N, P, Cu and Zn excretion.

Recommended requirements of Cu and Zn for growing-finishing pigs vary substantially between different countries. No definitive answer could be obtained if and how much the requirements should be enhanced at higher animal performance levels than documented in the literature.

By means of legislation on P in The Netherlands, excretion of P in manure of pigs has already decreased considerably. New technologies to supply the market compounds with a high availability for Cu and Zn look promising, and are necessary to comply with environmental and consumers' demands.

References

Aarnink, A.J.A., 1997. Ammonia emission from houses for growing pigs as affected by pen design, indoor climate and behaviour. PhD thesis, Wageningen, The Netherlands, 175 pp.

Anonymous, 2006. www.nmp.nl/mnp/i-nl-0082.html.

Bakker, G.C.M., Smits, M.C.J., Beelen, G.M., Jongbloed, A.W., 2004. De additiviteit van voedingsmaatregelen om de ammoniakemissie te verlagen uit varkensstallen. Proef 1: Balansmetingen en in vitro ammoniakemissie. Rapport 03/0000010, Nutrition & Food ASG-WUR, Lelystad.

Boer, F. de, 1980. Food waste disposal in Dutch livestock husbandry. Livest. Prod. Sci. 7, 39-48.

Bohlke, R.A., Thaler, R.C., Stein, H.H., 2005. Calcium, phosphorus, and amino acid digestibility in low-phytate corn, normal corn, and soybean meal by growing pigs. J. Anim. Sci. 83, 2396-2403.

BREF, 2006. IPPC Reference Document on best available techniques for intensive rearing of poultry and pigs. EC, July 2006.

BSAS, 2003. Nutrient Requirement Standards for Pigs. British Society of Animal Science, Penicuik, United Kingdom.

Canh, T.T., 1998. Ammonia emission from excreta of growing pigs as affected by dietary composition. PhD thesis, WIAS, Wageningen, The Netherlands, 163 pp.

Canh, T.T., Aarnink, A.J.A., Mroz, Z., Jongbloed, A.W., Schrama, J.W., Verstegen, M.W.A., 1998. Influence of dietary calcium salts and electrolyte balance on urinary pH, slurry pH and ammonia volatilisation from slurry of growing-finishing pigs. Livest. Prod. Sci., 56:1-13.

C.B.S., 2002. Milieucompendium 2001, Kluwer, Alphen aan de Rijn, The Netherlands.

CEN, 2003. CEN standard 13725. Air Quality – Determination of odor concentration by dynamic olfactometry. European Committee for Standardization. Brussels, Belgium.

Cnockaert, H., Sonck, B., 2007. Effect of different feeding strategies on the ammonia emission from a fattening pig house. In: Ammonia conference abstract book (G.J. Monteny, E. Hartung, M. van den Top and D. Starmans, Eds.), p. 72-73.

Cosgrove, D.J., 1980. Inositol phosphates. Their chemistry, biochemistry and physiology. Elsevier Science Publishers, Amsterdam, 175 pp.

Dilger, R.N., Adeola, O., 2006. Estimation of true phosphorus digestibility and endogenous phosphorus loss in growing pigs fed conventional and low-phytate soybean meals. J. Anim. Sci. 84, 627-634.

Dijkstra, E., Thissen, J., Jongbloed, A.W., 2008. Quantification of the effect of microbial phytase on the absorbability and bioavailability of Cu and Zn to reduce Cu and Zn emission by pigs and poultry to the environment. Report ASG (in press).

Dourmad, J.Y., Seve, B., Latimier, P., Boisen, S., Fernández, J., Peet-Schwering, C. van der, Jongbloed, A.W., 1999. Nitrogen consumption, utilization and losses in pig production in France, The Netherlands and Denmark. Livest. Prod. Sci. 58, 261-264.

Eckel, H., U. Roth, H. Döhler, F. Nicholson and R. Unwin (eds.), 2005. Assessment and reduction of heavy metal input into agro-ecosystems. Final report of the EU-Concerted Action AROMIS. KTBL publication no. 432, Darmstadt, Germany.

EU, 1991. Council directive 91/676/EEC of 12.12.1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources. ec.europa.eu/environment/water/water-nitrates/index_en.html.

EC, 1992. Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. Official Journal L 206 , 22/07/1992 P.

EC, 2000. Directive 2000/60/EC. Establishing a framework for Community action in the field of water policy. Official Journal of the European Communities L 327. ec.europa.eu/environment/water/water-framework/index_en.html.

EC, 2002. Regulation (EC) No 1774/2002 of the European Parliament and of the Council of 3 October2002 laying down health rules concerning animal by-products not intended for human consumption. http://europa.eu/scadplus/leg/en/lvb/f81001.htm.

EU, 2003. Commission regulation (EC) No 1334/203 of 25 July 2003. Amending the conditions for authorisation of a number of additives belonging to the group of trace elements. L 187/11-L 187/15. eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2006:339:0016:0035:EN:PDF.

EC, 2004. Directive 2004/35/CE of the European Parliament and of the Council of 21 April 2004 on environmental liability with regard to the prevention and remedying of environmental damage. ec.europa.eu/environment/liability/index.htm

EC, 2006. Directive 2006/12/EC of the European Parliament and of the Council of 5 April 2006 on waste. ec.europa.eu/environment/waste/legislation/a.htm

ec.europa.eu/environment/nature/legislation/habitatsdirective/index_en.htm.

Everts, H., Dekker, R.A., 1994. Effect of nitrogen supply on the retention and excretion of nitrogen and on energy utilization of pregnant sows. Anim. Prod. 59, 293-299.

GfE, 2008. Recommendations for the supply of energy and nutrients to pigs. DLG-Verlag, Frankfurt am Main, Germany.

Gothenburg, 1999. http://www.unece.org/env/lrtap/status/lrtap_s.htm.

Honeyman, M.S., 1996. Sustainability issues of U.S. swine production. J. Anim. Sci. 74, 1410-1417.

Hobbs, P.J., Pain, B.F., Kay, R.M., Lee, P.A., 1996. Reduction of odorous compounds in fresh pig slurry by dietary control of crude protein. J. Sci. Food Agric. 71, 508-514.

INRA, 1989. L'alimentation des animaux monogastriques: porc, lapins, volailes, Institut National de Recherches Agronomiques, Paris, 282 p.

Jondreville, C., Dourmad, J.Y., 2005. Phosphorus in pig nutrition. INRA Prod. Anim. 18, 183-192.

Jongbloed, A.W., Kemme, P.A., 1990. Apparent digestible phosphorus in the feeding of pigs in relation to availability, requirement and environment. 1. Digestible phosphorus in feedstuffs from plant and animal origin. Neth. J. Agric. Sci. 38, 567-575.

Jongbloed, A.W., Poulsen, H.D., Dourmad, J.Y., Peet-Schwering, C.M.C. van der, 1999. Environmental and legislative aspects of pig production in The Netherlands, France and Denmark. Livest. Prod. Sci. 58, 243-249.

Jongbloed, A.W., Kemme, P.A., Mroz, Z., Diepen, J.Th.M. van, 2000. Efficacy, use and application of microbial phytase in swine production. a review. In: Biotechnology in the Feed Industry, Proc. of Alltech's 16th Annual Symposium, T.P. Lyons and K. Jacques (Eds). Nottingham University Press, Nottingham, United Kingdom, p. 111-129.

Jongbloed, A.W., Diepen, J.Th.M. van, Kemme, P.A., 2003. Phosphorus requirements of pigs revision 2003 (In Dutch). CVB documentation report nr. 30, CVB, Lelystad, The Netherlands, 64 pp.

Jongbloed, A.W., Diepen, J.Th.M. van, Kemme, P.A., Broz, J., 2004a. Efficacy of microbial phytase on mineral digestibility in diets for gestating and lactating sows. Livest. Prod. Sci. 91, 143-155.

Jongbloed, A.W., Kemme, P.A., Top, A.M. van den, 2004b. Background of the copper and zinc requirements for dairy cattle, growing-finishing pigs and broilers. Report 04-0000635.

Jongbloed, A.W., 2006. Feeding strategies to reduce nitrogen and mineral excretion in pigs. In: IV Jornadas Internacionais Suinicultura, 12 and 13 May 2006, UTAD, Vila Real, Portugal, pp. 139-155.

Jongbloed, A.W., Kemme, P.A., 2007. Considerations on environmental impact of minerals in manure from pigs: strategies to minimise environmental load by nutrition and management. In: Taylor-Picard, J. and Spring, P. (editors), Gaining the edge in pork and poultry production, Wageningen Academic Publishers, Wageningen, the Netherlands, 71-100.

Jongbloed, A.W., Aarnink, A.J.A., Peet-Schwering, C.M.C. van der, 2007. Nutritional options to reduce ammonia emission from excreta of pigs. In: Ammonia conference abstract book (G.J. Monteny, E. Hartung, M. van den Top and D. Starmans, Eds.), p. 69-71.

Kemme, P.A., Jongbloed, A.W., Mroz, Z., and Beynen, A.C., 1997b. The efficacy of Aspergillus niger phytase in rendering phytate phosphorus available for absorption in pigs is influenced by their physiological status. J. Anim. Sci. 75, 2129-2138.

Kemme, P.A., Radcliffe, J.S., Jongbloed, A.W., Mroz, Z., 1997a. The effects of body weight, housing, and calculation method on mineral digestibility and the efficacy of microbial phytase in diets for growing-finishing pigs. J. Anim. Sci. 75, 2139-2146.

Kerr, B.J., Ziemer, C.J., Trabue, S.L., Crouse, J.D., Parkin, T.B., 2006. Manure composition as affected by dietary protein and cellulose concentrations. J. Anim. Sci. 84, 1584-1592.

Kies, A.K., Kemme, P.A., Sebek, L.B.J., Diepen, J.Th.M. van, Jongbloed, A.W., 2006. Effect of graded doses and a high dose of microbial phytase on the digestibility various minerals in weaner pigs. J. Anim. Sci. 84, 1169-1175.

Le, P.D., Aarnink, A.J.A., Ogink, N.W.M., Becker, P.M., Verstegen, M.W.A., 2005. Odor from animal production facilities: its relation to diet. Nutr. Res. Rev. 18, 3-30.

Le, D.P., 2006. Odor from pig production: Its relation to diet. PhD thesis, WIAS, Wageningen, The Netherlands, 206 pp.

Le, P.D., Aarnink, A.J.A., Jongbloed, A.W., Peet–Schwering, C.M.C. van der, Ogink, N.W.M, Verstegen, M.W.A., 2007a. Effects of dietary crude protein level on odour from pig manure. Animal 1, 734-744.

Le, P.D., Aarnink, A.J.A., Jongbloed, A.W., Peet-Schwering, C.M.C. van der, Ogink, N.W.M, Verstegen, M.W.A., 2007b. Effects of crystalline amino acid supplementation to the diet on odor from pig manure. J. Anim. Sci. 85, 791-801.

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

LEI, 2005. Agricultural statistics. www.lei.nl/statistics.

Lenis, N.P., 1989. Lower nitrogen excretion in pig husbandry by feeding: current and future possibilities. Neth. J. Agric. Sci. 37, 61-70.

Lester, J. Ammonia: a particulate matter precursor. www.airquality.nrcs.usda.gov/. ../San_Diego_2007/1_%20DR%20JULIA%20LESTER_MAY%202007%20AAQTF--Ammonia.pdf.

Novoselova, T.A., 2007. Analysis of adoption of genetic modification in pork production chains. PhD thesis Agricultural University Wageningen, The Netherlands.

NRC , 1998. Nutrient requirements of swine. National Academy of Sciences, National Academy Press, Washington (DC), USA, 93 pp.

Oenema, O., 2004. Governmental policies and measures regulating nitrogen and phosphorus from animal manure in European agriculture. J. Anim. Sci. 82(. Suppl.), E96-E206.

Otto, E.R., Yokoyama, M., Hengemuehle, S., Bermuth, R.D. von, Kempen, T. van, Trottier, N.L., 2003. Ammonia, volatile fatty acids, phenolics, and odor offensiveness in manure from growing pigs fed diets reduced in protein concentrations. J. Anim. Sci. 81, 1754-1763.

Pentington, N., 2008. Environmental expectations – what has the pig industry to achieve. Manuscript Forum Nutrition Conference, 29 April 2008, Birmingham.

Powers, W., Zamzow, S., Kerr, B., 2007. Effect of die ton air emissions from pigs. In: Ammonia conference abstract book (G.J. Monteny, E. Hartung, M. van den Top and D. Starmans, Eds.), p. 74-75.

Rademacher, 2000. How can diets be modified to minimize the impact of pig production on the environment? Amino News, Special issue 1, Degussa-Hüls

Revy, P.S., Jondreville, C., Dourmad, J.Y., Nys, Y., 2004. Effect of zinc supplemented as either an organic or an inorganic source and of microbial phytase on zinc and other minerals utilization by weanling pigs. Anim. Feed Sci. Technol. 116, 93-112.

Revy, P.S., Jondreville, C., Dourmad, J.Y., Nys, Y., 2006. Assessment of dietary zinc requirement of weaned piglets fed diets with or without microbial phytase. J. Anim. Physiol. Anim. Nutr. 190, 50-59.

Spencer, J.D., Allee, G.L., Sauber, T.E., 2000. Phosphorus bioavailability and digestibility of normal and genetically modified low-phytate corn. J. Anim. Sci. 78, 675-681.

Staatscourant, 2004 (22-12-2004, nr. 247, page 34). [Legislation environmentally quality requirements dangerous compounds surface waters] Regeling milieukwaliteitseisen gevaarlijke stoffen oppervlaktewateren, nr. MJZ2004128920, 10-12-2004, p. 1-82.

Staatscourant, 2006 (18-12-2006, nr. 246, page 21). [Legislation odour nuisance in livestock farming] Regeling geurhinder en veehouderij, p. 1-6.

Sutton, A.L., Kephart, K.B., Verstegen, M.W.A., Canh, T.T., Hobbs, P.J., 1999. Potential for reduction of odorous compounds in swine manure through diet modification. J. Anim. Sci. 77, 430-439.

Van Heughten, E., Kempen, T.A.T.G. van, 2002. Growth performance, carcass characteristics, nutrient digestibility and fecal odorous compounds in growing-finishing pigs fed diets containing hydrolyzed feather meal. J. Anim. Sci. 80, 171-178.

Visser, H., E. Buringh, and P. B. Breugel. 2001. Composition and origin of airborne particulate matter in The Netherlands. RIVM Report 650010029, RIVM, Bilthoven, 104 pp.

Van Vuuren, A. M., Jongbloed, A. W., 1994. General plan for the role of feeding measures to restrict ammonia emission from livestock buildings (In Dutch), Report ID-DLO (IVVO) No. 272, Lelystad, The Netherlands.

Willig, S., Lösel, D., Claus, R., 2005. Effects of resistant starch on odor emission from faeces in swine production facilities. J. Agric. Food Chem. 53, 1173-1178.