New Technologies in Low Pollution Swine Diets : Diet Manipulation and Use of Synthetic Amino Acids, Phytase and Phase Feeding for Reduction of Nitrogen and Phosphorus Excretion and Ammonia Emission* - Review -

Nico P. Lenis[1] and Age W. Jongbloed
Institute for Animal Science and Health (ID-DLO), Department of Pigs and Poultry,
P.O. Box 65 Lelystad, 8200 AB, The Netherlands

ABSTRACT : In the paper insight is given in the legislation policy to restrain environmental pollution by pig husbandry, focused on The Netherlands (Mineral Accounting System). Besides, nutritional measures are presented to reduce environmental pollution by lowering excretion of N and P, emphasizing (multi) phase feeding, the use of low protein, synthetic amino acids supplemented diets, phytase and its effect on phosphorus and calcium digestibility, its interaction with phytic acid and proteins, and the environmental impact of the use of phytase in pig diets. Also, nutritional means are indicated to reduce ammonia volatilization from pig operations. It is concluded that nutrition management can substantially contribute to reduction of N and P excretion by pigs, mainly by lowering dietary protein levels, (multi) phase feeding and the use of microbial phytase, and that the use of phytase on a large scale in The Netherlands has a tremendous environmental impact. In 20 years the excretion of P in growing-finishing pigs has more than halved. Ammonia emission from manure of pigs can be reduced substantially by lowering dietary protein content, but also by including additional non-starch polysaccharides in the diet. A very promising method to reduce ammonia emission is to manipulate dietary cation-anion difference, e.g. by adding acidifying salts to the diet, which will lower pH of urine substantially. Further research is desirable. This also applies to determining dietary factors influencing the odour release from manure. Finally, some speculation on the future of pig farming from an environmental viewpoint is presented. *(Asian-Aus. J. Anim. Sci. 1999. Vol. 12, No. 2 : 305-327)*

Key Words : Pigs, Nutrition, Environment, Legislation, Minerals, Phytase, Ammonia Emission

INTRODUCTION

Environmental concerns as a result of agricultural production can be divided in those related to the soil (accumulation of nutrients; acid rain; drying out of ground water reserves; heavy metals and herbicides; erosion), to the surface and ground water (eutrophication) and to the air (global warming, odours, dust). The major challenge in several countries, not only in Europe and the USA but also in Asia (Watanabe, 1996; Sheen and Hong, 1998; Yano et al., 1998) is finding an acceptable balance between the input and output of N and minerals per hectare of cultivated land. Some minerals such as P, Cu and Zn accumulate in the soil and contribute via leaching and run-off to eutrophication of ground and fresh water sources and may cause excessive growth of algae, sometimes resulting in massive fish mortality (Roland et al., 1993).

Table 1 lists the contributions of phosphate (P_2O_5) from animal manure and fertilizers for some animal dense provinces and for the whole Netherlands (CBS, 1995).

Considering that crops use an average of 21.9 kg P (50 kg P_2O_5) per hectare, it is apparent that, in The Netherlands, P accumulates in the soil. Also heavy metals accumulate in the top layer with consequences for plant growth and potential risks for human and animal health (e.g., copper intoxication of sheep; Henkens, 1975), and soil life (earth worms, microbes; Van Rhee, 1974). Furthermore, the loss of organic matter in the soil predominantly due to erosion may also be regarded as a major environmental threat (Pimentel et al., 1995).

Table 1. Amount of P_2O_5 in animal manure and fertilizers in The Netherlands (kg/ha cultivated land)

Province/Country	1970	1980	1987	1990	1995
Noord Brabant	110	195	245	200	204
Gelderland	115	170	200	175	162
Limburg	110	165	215	160	174
Netherlands (manure)	78	114	124	110	107
Netherlands (fertilizer)	49	42	44	38	32
Netherlands (total)	127	156	168	148	139

Because of excessive application of manure and fertilizers per hectare of land, surplus precipitation and leaching, nitrate often exceeds tolerable values in fresh water (50 mg nitrate/L). Similarly, the tolerated level of 12 mg K/L of fresh water is exceeded, although it is not clear at this moment what are its environmental consequences (Van Boheemen et al., 1991). Apart from accumulation, heavy metals may also leach to the ground water considerably (Van Erp and Van Lune, 1991). Because it is common practice in some countries

[1] Address reprint request to N. P. Lenis (E-mail: n.p.lenis@id.dlo.nl).

* This paper has been presented at Pre-Conference Symposium I entitled "Recent Advances in the Production of High Quality Pork" at the 8th World Conference on Animal Production on June 28, 1998 at Seoul National University, Seoul, Korea. The paper has been reviewed and edited by Prof. P. Bosi (Italy) and Prof. Y. I. Choi (Korea).

to supplement post-weaning diets for piglets with 2000 to 3000 ppm Zn, accumulation and leaching of Zn may increase considerably. In The Netherlands, Cd , Cu and Zn are regarded as the most threatening metals. Therefore, as in many other countries, heavy metal excretion by livestock should be further reduced in The Netherlands.

In pig manure the major part of nitrogen originates from urea excreted with the urine. Ammonia emission from manure originates primarily from this urea. Nitrogen in the faeces comprises undigested dietary N and endogenous N, and microbial N. Due to the urease activity of faecal microbes, urea is rapidly converted into ammonia which easily volatilizes into the air. In the soil due to nitrification, ammonia which is in equilibrium with ammonium, is converted to nitrate together with the formation of two atoms of hydrogen. Ammonia and gases like SO_2, and NO_x may lead to acidification of the soil. The aerial pollution, with ammonia and greenhouse gases, together with odours are also of concern. Animal husbandry causes 92% of the total NH_3 emission in The Netherlands (Heij and Schneider, 1995). The emission of CH_4, primarily from ruminants, and gases like N_2O contribute to global warming (green house effect) by 15-20% and 6%, respectively (Leijen et al., 1993;Watanabe, 1996). There is only a small contribution to CO_2 emission from pork production (1%) in The Netherlands. Concerning methane in dairy cows, increasing milk production per cow by feeding more concentrates is considered as the best method to decrease methane production per kg milk (Watanabe, 1996). Further research is desirable to suppress methanogenesis. Dust, noise, visual pollution, and animals and their manure as carriers of pathogens, may also be regarded as environmental concern. Furthermore, the loss of organic matter in the soil predominantly due to erosion may also be regarded as one of the major environmental threats (Pimentel et al., 1995).

Generally, the enrichment of the environment may lead to less biodiversity. This aspect is stressed more and more in The Netherlands. The negative impact of livestock production on the environment has already led to legislation in some European countries (Jongbloed et al., 1998), a few states in the USA (Lorimor and Melvin, 1996) and Japan (Watanabe, 1996) that limit the use of animal manure or the number of animals per hectare of cultivated land.

In the paper insight is given in the legislation policy to restrain environmental pollution by pig husbandry, focused on The Netherlands (MINeral Accounting System). Besides, nutritional measures are presented to reduce environmental pollution by lowering excretion of N and P, emphasizing (multi) phase feeding, the use of low protein, synthetic amino acids supplemented diets, phytase and its effect on phosphorus and calcium digestibility, its interaction with phytic acid and proteins, and the environmental impact of the use of phytase in pig diets. Also, nutritional means are indicated to reduce ammonia volatilization from pig operations.

LEGISLATION IN THE NETHERLANDS

A disturbed mineral balance in several soils in The Netherlands was recognized as early as the 1970s by several experts (Jongbloed and Henkens, 1996), but legislation was not enforced until 1984. Global aims of governmental policies in The Netherlands and in other European countries are mainly based on the directive from the European Union (1991) for the protection of water quality.

Legislation 1984

Legislation was enforced in The Netherlands to achieve 1) equilibrium in fertilizer application, 2) reduction of acid deposition, and 3) protection of surface and ground water quality. With respect to soil protection, the policy stated that in the long term, no harm to plant growth or health risk for humans and animals was permitted. In the same year, a freeze was placed on pig and poultry expansion.

Criteria formulated for N stated that the concentration of nitrate in ground and surface water should not exceed 50 and 10 mg/L, respectively. Moreover, surface water should not contain more than 0.02 mg of NH_3 N per liter. Furthermore, NH_3 emission should be reduced by 50% in the year 2000 relative to 1980. From 1992, all manure pits should be covered. For P, the ground and surface water should not exceed 0.10 mg of *ortho*-P per liter (about 0.15 mg of P_t per liter). Local authorities can urge additional restrictions, especially when the farms are located close to woods or natural parks.

The amount of animal manure that could be applied per hectare of land was based on its P content (table 2).

Table 2. Allowed application of P_2O_5 (kg/ha) from 1987 onwards in the Netherlands

	Grassland	Arable land	Corn silage
1990	250	125	350
1991-1993	200	125	200
1994	200	125	150
1995	150	110	110
1997	135	110	110

The allowed application was gradually reduced for all types of land, which resulted in an amount of 110 kg of P_2O_5 for both arable land and land used for corn silage and 135 kg for grassland. In order to reduce leaching of nitrate, application of manure on the field was restricted more during the autumn and winter, when there is no growth of crops. The application period also depends on the soil type and crop. Additionally, restrictions were made with regard to the method of application. More use of the injection method or incorporation immediately after application was enforced to reduce ammonia emission. If the P_2O_5 production per hectare of cropland exceeded the amount allowed, the farmer had to pay a tax on the surplus, which had to be transported to other regions. Manure transport can be facilitated by use of the manure bank program.

1998 MINAS legislation

In January 1998, new MINAS legislation, which contains far-reaching amendments to earlier Dutch legislation, was introduced. The most drastic policy change is the introduction of compulsory mineral input and output registration for farms with more than 2.5 Livestock Units (LU) per hectare, of which there are about 50,000 in The Netherlands. The legislation is aimed at reducing the mineral surpluses and to achieve an equilibrium in fertilizer application, which means having a good balance between input and output and taking into account obligatory losses. Apart from phosphate, also nitrogen is included in the new legislation. The MINAS includes all animals to which manure legislation applies: cattle, pigs, chickens, turkeys, foxes, mink, goats, ducks, and rabbits. A level of 2.5 LU is equal to the number of animals that excrete 102.5 kg of manure phosphate per year. This might be 2.5 dairy cattle, 13.9 growing pigs, five breeding sows with piglets, or 427 broilers. Nearly all pig, poultry and other intensive farms exceed the limit of 2.5 LU per hectare. After the year 2000 all farms with livestock will have to participate in MINAS.

The farms exceeding 2.5 LU/ha must submit a minerals account each year. Farmers register how many kilograms of phosphate and nitrogen enter the farm and how many leave the farm. Main sources of input are, for instance, supply of animals, (compound) feed, fertilizers and animal manure from other farms. Main items of output are discharge of slaughter animals, milk, animal manure and crops. Because it is never possible to exactly balance inputs and outputs, some minerals are always lost. The regulation, therefore, prescribes a maximum allowable loss (standard losses or levy-free surpluses) for phosphate and nitrogen (table 3).

Table 3. Standard losses or levy-free surpluses of P (kg P_2O_5/ha) and N (kg/ha) in the Netherlands in the new 1998 MINAS legislation

Year	Grassland and arable land P	Grassland N*	Arable land N*
1998	40	300	175
2000	35	275	150
2002	30	250	125
2005	25	200	110
2008/2010	20	180	100

* deposition and mineralization not included

Levy-free surpluses per hectare for phosphate and nitrogen are rather stringent and will be lowered in increments. Levy-free surplus for P for each hectare of arable land and grassland will gradually decrease from 40 kg P_2O_5 per hectare in 1998 to 20 kg in the year 2008/2010. For grassland the levy-free surplus for N will decrease from 300 to 180 kg per hectare. An evaluation will be held in the year 2000, after which the standard losses may be changed. In addition to the standard losses per hectare, there is also a correction for nitrogen losses per animal because of ammonia volatilization in livestock housing. When drawing up a minerals account, farmers may deduct the levy-free surpluses and the corrections from their minerals account. As a temporary measure in 1998 and 1999 the input of phosphate fertilizer will not be changed in MINAS, although it needs to be accounted for. With the implementation of MINAS, the surplus levy from the 1984 legislation has become obsolete. Instead, in 1998 and 1999 farmers whose nitrogen and phosphate losses exceed the maximum have to pay levies of US$ 1.25 per kg for the first 10 kg of phosphate surplus per hectare and US$ 5 for each successive kg. From the year 2000, these levies will be US$ 2.50 and US$ 10, respectively. The levy for N surplus will be US$ 0.75 per kg per hectare. In addition, MINAS participants will have to pay destination levies at a fixed rate of US$ 200, though some form of discount may be possible. For specialized pig and poultry farmers, having no or little land, the main costs due to MINAS legislation will probably be costs for discharging, sampling, and analyzing the manure. The costs of selling manure to arable farms will depend on supply and demand. The amounts of P_2O_5 and N in the manure will be very decisive; however, discharging manure from the farm probably will result in substantial costs.

Livestock farmers who are required to submit a minerals account according to MINAS have two options: 1) a specific account or 2) an estimated account. A specific minerals account is an accurate registration of the quantities of phosphate and N entering and leaving the farm. Farmers should also consider the additional costs for sampling, weighing and administration. However, a specific account gives a more accurate picture of the mineral inputs and outputs and is usually fairer than the current system of manure accounting. An estimated account is simpler and less costly, but it is also less accurate and carries more disadvantages than the specific method. The estimated account is a calculation based on official, fixed rates. These rates are used to calculate the quantities of phosphate and N in manure and other fertilizers. Standard losses and N corrections are then deducted from this amount. There is also a fixed deduction for minerals output through crops. In the regulation, the official rates are deliberately higher than the average real-life situation to encourage farmers to choose in favor of specific accounting.

Farms with less than 2.5 LU per hectare will not be required to keep the new minerals accounting system MINAS up to the year 2000. However, these farmers will have to keep a monthly record of the number of animals and the quantity of land. Besides, they have to calculate the phosphate production from their animals per year. Phosphate from the herd and from animal manure from other farms must be totalled. The farmers have to make sure they do not apply excessive amounts of phosphate to their own land. The allowed quantities for application per hectare of land for 1998 and 1999 are 120 kg of phosphate on grassland and 100 kg on arable land. When these quantities are exceeded, a farmer must submit a minerals account after the fact based on fixed rates. Typically, this will result in the paying a levy. Specialised arable and horticulture farms without livestock only have to register the amount of land and the quantities of animal manure and other organic fertilizers brought in from outside. They may not exceed the input standards per hectare for animal manure. If they do, they are required to submit a minerals account. In the year 2002 arable and horticulture farms will have to participate in MINAS.

Small farms with no more than 3 LU and less than 3 ha of land are not required to register their land and animals. However, evidence of manure transports must be recorded. This category also includes small horticulture farms. Different rules apply for greenhouse horticulture.

Apart from the minerals accounting system, a set of measures which has proved its effectiveness in the past will become applicable to all farms as a basic package. It contains the following measures:

1) a ban on spreading manure in autumn and winter (September 1 to February 1) for leaching-prone grassland and arable land; for grassland not prone to leaching, starting on September 15;

2) when spreading manure to make use of techniques that keep ammonia emission to a minimum (injection method or incorporation immediately after application);

3) to cover manure stores built after 1987.

At the end of 1998 it became clear that the European Union (EU) is of the opinion that the Dutch MINAS policy is still not sufficient to meet the obligations on the Nitrates Directive (nitrate concentration in the upper groundwater should be below 50 mg/L). Objections of the EU are that the standard losses for nitrogen in MINAS are too high (it turns out that in 1998 and 1999 many farmers can meet the standard losses) and that by simply paying a levy the nitrate situation in the groundwater will not improve. So, additional measures are needed to reduce the nitrogen load. Probably the Dutch government will decide to change the regulations for standard losses, e.g., to decrease the standard losses for nitrogen quicker, to forward the final standard losses of the year 2008/2010 to the year 2005, and to lower the final standard nitrogen loss on sandy soils, susceptible for nitrate leaching: on grassland from 180 to 140 kg per hectare and on arable land from 100 to 60 kg per hectare. Arable and horticulture farms will be obliged to participate in MINAS in the year 2001 instead of 2002. Besides the government, forced by the EU, will probably decide to maximize all farms with livestock to 2.5 LU/ha or even less in the year 2008, and probably already in 2005 for the farms on nitrate leaching susceptible soils. The EU considers this as the best guarantee for a low nitrogen loss. A special policy will be developed for areas from which drinking water is withdrawn.

DUTCH PIG RESTRUCTURING LAW

Following the problems of swine fever in The Netherlands in 1997 a radical pig restructuring law to reduce Dutch pig production by 25%, or 10-11 million animals, by the end of the year 2000 has been approved in Dutch Parliament by early 1998, and came into force by September 1, 1998. In outlining a radical reform to prevent the rapid spread of the disease in the future, the government took the opportunity to try and to address the underlying structural problem of highly intensive production concentrated in the south and east of the country, as well as environmental and animal welfare concerns.

After warnings from the European Union that the planned restructuring was not compatable with EU-regulations, the government took the environmental rather than the veterinary/agricultural approach and informed the EU that the proposed measures were linked to Dutch obligations on the Nitrates Directive.

The scheme foresees a 10% reduction in all individual production rights by the end of 1998, and a further cut by the end of the year 2000. The final legislation has provided a certain amount of flexibility for some producers, but despite widespread lobbying, there will be no compensation paid to any of the 20000 pig holdings in The Netherlands for the reduction in pig production rights. Pig producers will be allowed to choose between 1995 and 1996 as the reference year for the reduction, i.e. before the outbreak of swine fever. There is also flexibility on the percentage reduction applicable for producers using environmentally friendly methods, e.g., a 5% exemption for the 25% reduction if low phosphate feed is used and adequate manure disposal measures are provided. In order to prevent speculative trade in pig producer rights between 1998 and 2000, the government legislation also limits the sale of pig production rights of each holding considerably. The government will make US$ 235 million available in the first two years of the scheme as restructuring aid.

Because of the very bad financial situation and prospects in the Dutch pig husbandry sector, due to the consequences of the swine fever in 1997, the extremely low prices for pork meat in 1998 and high investments by the farmers for animal welfare regulations, the Dutch government has declared at the end of 1998 to consider to skip the second general reduction of all individual production rights by the end of the year 2000. When keeping the policy goals of the restructuring law, this could be achieved by buying, not by taking, 1 to 1.5 million pig production rights from farmers.

LEGISLATION IN FRANCE AND DENMARK

Distinct differences in legislation exist in France and Denmark, compared to The Netherlands, as has been summarized by Jongbloed et al. (1998) (see also table 4)

Table 4. Legistration in France, Denmark and The Netherlands

F	maximum of 170 kg N from manure per ha maximum of 43.8 kg P per ha (100 kg P_2O_5 per ha, only in the Vendée region)
DK	maximum of 1.7 animal unit per ha (equal to 51 fatteners or 5.1 sows incl. piglets to 25 kg)
NL	maximum of 52.6 kg P (120 kg P_2O_5) per ha grassland or 43.8 kg P (100 kg P_2O_5) per ha of arable land surplus of N/ha in 1998 300 kg and in 2008 180 kg/ha

In France the amount of N from animal manure should not exceed 170 kg/ha, with some specific limitations around water wells and along rivers. Farmers can exceed the animal density limitation, provided that an agreement is made with neighbouring farms with additional land, or that a treatment of the manure is performed that reduces its N load. Phosphorus is not yet in the French legislation except for the Vendée departement where the amount of P should not exceed 100 kg P_2O_5 per ha. The amount of N and P in the manure before spreading are determined according to the number of reproductive sows or number of pigs produced per year (Corpen, 1996). Three ways of calculation are used depending on the feeding strategy (standard values, two phase feeding system values, and a simplified balance method). In Denmark, restrictions on animal density were imposed together with improved utilization of N from pig manure. The current legislation permits the delivery of pig manure from 1.7 animal units per ha arable land. One animal unit corresponds to the manure production of 30 growing-finishing pigs (25-95 kg) or 3 sows (including their yearly production of piglets up to 25 kg). It is expected that, from December 1999, one animal unit will be equivalent to maximum 100 kg manure-N produced (measured ex storage). Farmers can exceed the animal density limitation, provided that an agreement is made with neighbouring farmers. Production of more than 250 animal units requires approval of special procedures. In all cases, it is required that the farmer owns a fixed proportion of the land required. The proportion is dependent on the number of animal units. Danish regulations for the application period of manure on the field are similar to the Dutch regulations.

REDUCTION OF EXCRETION OF N AND P BY PIGS BY ALTERING NUTRITION AND FEEDING

The Netherlands was the first to initiate a large research programme to reduce environmental pollution by livestock production. Three main solutions were proposed. The first one was a reduction of input of minerals via the feed. The second one was a stimulation of practical solutions at farm level such as distribution and application of manure. The third solution was to upgrade manure by processing on a large scale for export purposes. Costs of the research program was financed by the government and animal-related commodities. The various nutrition-related projects were supervised both by members of research institutes and the feed industry. The advantage of such supervision is that application of the results were not delayed.

So far, the approach of feeding and nutrition has been the most successful, as will be summarized in this chapter. The same approach has been succesful for poultry. At the end of 1994, it became clear that processing of manure on a large scale was too expensive to be implemented as a tool for reducing surplusses of manure by export.

Nutritional research aimed to alleviate the manure problem has focused mainly on reducing the dietary input of N and P, and on their more efficient utilization. Growing pigs use only about 30 to 35% of ingested dietary N and P (Jongbloed and Lenis, 1992). For this reason it is important to supply dietary N and P in close accordance with the animals' requirement. This requires adequate knowledge about the digestibility of amino acids (AAs) and P in the feed used, and on the requirement for these nutrients. Requirements in different countries may vary because of differences in housing conditions, genotype of animals, level of feeding, major ingredients used in the diets and response criteria. Furthermore, it is possible to enhance the digestibility of P in feeds by using extrinsic enzymes. In addition, the excretion of N and P can further be reduced by exchanging less digestible feedstuffs by better digestible ones. Also, by improved performance (improved types of pigs) reduction of the excretion of N and P can be substantially. In this respect also optimal management with regard to housing and health status of the pigs and feeding strategy, which may improve feed conversion ratio, will be beneficial for the environment.

Supplementation of feed additives (growth promoters) may also reduce excretion of N and P as a result of a better feed conversion ratio as compared to non-supplemented feeds. Jongbloed (1992) estimated that the excretions of N and P per weaned piglet and growing pigs were 7 and 3%, respectively, higher when no feed additives were used.

Unfavourable feed conversion ratios in castrates compared with boars can be improved with beta-agonists which shift from fat to lean meat production

(Berschauer, 1990). Both N and P excretion can be further reduced with recombinant porcine somatotropin (rPST) as shown by Noblet et al. (1993). Permission to use rPST or beta-agonists is very doubtful in The Netherlands because of consumers attitude.

SUPPLY N AND P FOR PIGS IN BETTER AGREEMENT WITH THEIR REQUIREMENT

Supply of digestible amino acids and P

1) Amino acid digestibility

In The Netherlands, protein is evaluated by the ileal digestibility of AAs. Therefore, protein requirements are based on the apparent ileal digestibility of lysine, methionine, cystine, threonine, and tryptophan (CVB, 1998; Lenis, 1992). Because it is increasingly recognized that the calculation of apparent digestibility entails a systematic under-estimation of protein and amino acid digestibility of lower protein feedstuffs, in the new Dutch Feedstuff Table (CVB, 1998) the apparent ileal digestibility values of (all) amino acids for feedstuffs are based upon the so called standardized ileal digestibility, in which is corrected for the influence of basal (non-specific) AA losses according to dry matter intake, as suggested by Mariscal-Landin (1992) and recently adopted by Eurolysine/ITCF (Jondreville et al., 1995). In contrast to apparent ileal digestibility values, the standardized values are independent of the inclusion level of the feed ingredients (and the protein content) in the diet. In the new Dutch system information about the amount of basal endogenous crude protein and its amino acid composition, based on the N-free method, has been taken from Jansman et al. (1997). Data on the ileal digestibility coefficients for some feedstuffs, calculated in this way, are provided in table 5.

2) Phosphorus digestibility

From our preliminary experiments we noticed that total P content of a diet did not reflect its nutritive value correctly. Therefore its P digestibility should be measured. In literature different terms are used to determine nutritive value of minerals for pigs, e.g., digestibility, absorbability or (bio-)availability. The digestibility and absorbability refer to the gastrointestinal tract (feed-faeces). The term (bio-)availability, however, is used with different meanings, and can therefore be misleading. As in our technique with pigs at ID-DLO we measure the net absorption of minerals, we do not prefer to use the term availability, but we will use the term (apparent) digestibility to strengthen practical understanding and interpretation in one way.

Table 5. Ileal digestibility of N and some AAs (%), calculated on the basis of standardized ileal digestibility in some feedstuffs (CVB, 1998)

Feedstuff	N	Lys.	Met.	Cys.	Thr.	Tryp.
Barley	71	67	77	73	65	68
Maize	71	60	81	72	61	52
Wheat	80	74	85	83	72	78
Peas	74	79	69	62	69	64
Wheat middlings	71	73	78	71	63	76
Soybean meal (extr)	84	88	88	81	83	85
Sunflower meal (extr)	77	76	86	74	76	80
Meat meal (fat)	72	76	75	47	72	70

We developed two procedures to measure the nutritive value of P based on its apparent digestibility. The first one is ascribed for feedstuffs from plants (Jongbloed and Kemme, 1990), and the second for feedstuffs originating from animals or in feed phosphates. The principle of the first method is as follows:

For each trial four pigs are used from 40 to 110 kg liveweight (LW) in a Latin square design. In the trials a basal feed is used except for the cereals (barley, maize, wheat), which are tested as a single feed. For the other

Table 6. P digestibility coefficients (% of intake) of some feedstuffs from plant origin for pigs

Feedstuff	P(g/kg)	Phytate P (g/kg)	Number of trials	Mean	SD	Range
Barley	3.6	2.5	5	39	4	34-44
Maize	2.9	2.0	10	19	6	12-26
Wheat	3.4	2.2	4	48	2	46-51
Wheat inact.*	3.4	2.2	2	26	1	26-27
Peas	3.7	2.3	4	45	4	42-51
Beans	4.7	2.4	3	37	8	29-48
Lupins	3.9	2.3	3	50	4	47-56
Tapioca	0.8	0,2	4	6	5	1-13
Hominy feed	5.1	3.8	8	21	8	13-34
Rapeseed extr.	10.9	8.2	3	27	4	22-33
Rice bran	15.4	13.9	6	14	4	9-20
Soybean meal extr.	6.3	4.4	9	39	4	33-46
Sunflower meal extr.	12.1	10.9	10	15	4	9-20
Wheat bran	12.8	10.9	3	30	5	24-35
Coconut expeller	5.4	2.7	4	33	7	25-44
Maize gluten feed	9.2	6.4	11	20	6	12-32

* intrinsic phytase inactivated by thermal treatment

Table 7. P digestibility coefficients (% of intake) of some feedstuffs from animal origin and feed phosphates

Feedstuff	Ca (g/kg)	P (g/kg)	Number of trials	Mean	SD	Range
Bone meal	166	77	1	74	-	-
Bone precipitate A	229	176	1	87	-	-
Bone precipitate B	258	197	1	61	-	-
Skimmilk dry	13	10	1	90	-	-
Fish meal	43	27	2	72	17	61-84
Meat+bone meal	147	69	2	81	1	80-81
Dicalcium P.0H_2O (A,B)	250	200	4	64	2	63-66
Dicalcium P.2H_2O (A,B)	240	182	3	69	1	69-71
Monocalcium P.1H_2O(A)	160	226	3	75	3	72-78
Monoclcium P.1H_2O(B)	160	226	4	82	2	80-84
Calcium sodium P	311	181	2	85	2	84-86
Mono sodium P.2H_2O(ref.)	-	225	3	90	3	88-93

A and B are from different production processes ref.= reference chemically pure monosodium phosphate

feedstuffs tested, maize is used as a basal feed, because of the low total P and digestible P content. About 50% or more of the tested feedstuff should be used in addition to the basal diet, provided that the concentration of digestible P does not exceed 1.6 g/kg of feed. This amount is found to be the minimum P requirement for growing pigs. When feeding below the pig's P requirement, maximal digestion of P takes place. To balance the feeds, all vitamins and trace minerals are added in amounts that are recommended for common practice.

The principle of the second method is as follows (Dellaert et al., 1990). In this method we use piglets from five to ten weeks of age, with a more or less practical basal diet with a low content of digestible P (1.2 g/kg). With these piglets it is possible to supply 2.0 g P/kg from the source to be tested. In case of animal products their contribution to the protein supply is taken into account. Calcium level of all diets is fixed at 7.5 g/kg. There are three or four replicates per treatment. Mostly in the third, fourth, and fifth week of study grab samples of faeces are taken according to a standard procedure. So far, we have assessed the apparent digestibility of P in more than 150 batches of feedstuffs. Results of these experiments are tabulated in the official Dutch Feedstuff Table (CVB, 1998) for practical usage, and can be regarded as the most advanced, when compared to NRC (1988) (USA) and DLG (1987) (Germany).

Results of the ID-DLO-experiments on P digestibility in feedstuffs from plant origin for pigs are listed in table 6. From table 6 can be concluded that relatively large differences in P digestibility are observed among feedstuffs. The lowest P digestibility was noted for tapioca meal and rice bran, whereas the highest values were obtained for lupins and wheat. The differences in P digestibility in conventional wheat and wheat with inactivated intrinsic phytase show that wheat phytase has a large effect (Pointillart, 1993). The large variation within a feedstuff is attributed to differences in phytate P content, phytase activity and processing (Jongbloed and Kemme, 1990).

One should realize that there are a lot of factors that affect mineral digestibility (Jongbloed, 1987). Dietary Ca content has, therefore, been standardized for assessing the P digestibility of feeds. This factor is also necessary to take into account when comparing literature data.

3) In vitro measurements on feed phosphates

There have been several attempts to determine the availability of P from inorganic P sources using chemical methods (Wicke, 1972; Guéguen, 1977; Jensen et al., 1977; Huyghebaert et al., 1980). It appears that solubility in water and in ammonium citrate are not good indicators of the availability of P for pigs. Guéguen (1977) proposed a method in which first the solubility in water is determined followed by extraction with a 2% citric acid solution. This method was applied for sheep, but it is not certain whether it is also suitable for pigs. Therefore, we applied solubility of the feed phosphates used in our experiments in water and citric acid and related it to the observed P digestibility (Kemme et al., 1993a). From the results it can be concluded that water solubility gives an underestimation of the availability of dicalcium phosphates, while citric acid solubility overestimates the P digestibility of all feed phosphates. Also recent research of Kornegay and Radcliffe (1997) showed that no relationship between solubility in neutral ammonium citrate and bioavailability of P sources could be demonstrated.

Effect of age and physiological status on P and Ca digestibility

Little is known concerning the effect of age or physiological status ot the animal on absorbability of minerals. Recently Kemme et al. (1997b) performed an experiment with starter pigs, growing-finishing pigs, and pregnant and lactating sows at ID-DLO to test the hypothesis that apparent P and Ca digestibilities depend on their physiological status. Pigs of the four categories were fed diets with identical feedstuff composition. The digestibility of P increased in starter piglets and growing-finishing pigs when bodyweight increased from 30 to 60 kg (23% and 26%, respectively) and then remained stable until 100 kg BW. This lack of an effect from 60 to 100 kg BW may be explained by the fact that the pigs requirement for P was nearly met at heavier weights. P digestibility in pregnant sows (14% at day 60) was lower than in the starter pigs and the growing-finishing pigs, but at the end of pregnancy and during lactation, P digestibility (18%-19%) was higher than during mid pregnancy. For Ca even larger differences were observed in digestibility between growing pigs and breeding sows.

Requirements for digestible amino acids and P

1) Amino acids

It is generally accepted that a starting point for AA requirement of pigs should be the concept of ideal protein. The first attempt to specify "ideal protein" for pigs was made by the ARC (1981). Reassessments of ideal protein have been reported by Moughan and Smith (1984), Wang and Fuller (1989), Fuller et al. (1989), Baker and Chung (1992), Lenis (1992), Batterham (1994) and Baker (1996, 1997). Lenis (1992) concluded from his experiments and from calculations on literature data that for maximum growth performance of growing-finishing pigs, the requirements for apparent ileal digestible methionine+cystine, threonine and tryptophan, relative to apparent ileal digestible lysine, should be 59, 63, and 19%, respectively (for threonine a correction factor (1.05) was used; if this correction is not applied, then the ileal digestible threonine requirement will be 60%). With regard to the methionine +cystine requirement there are indications that the methionine:cystine ratio in the diet should not be below 50% (Roth and Kirchgessner, 1989; Lenis et al., 1990). Recently, Lenis (1996) slightly modified apparent ileal digestible amino acid recommendations for Dutch growing pigs, considering the increasing contribution for maintenance of the sulfur amino acids (SAA) and threonine during the growing period (table 8).

Table 8. Recommended concentrations (g/kg) and amino acid ratios (in bold) of apparent ileal digestible amino acids for maximum performance in feeds for growing pigs (Lenis, 1996)

Feed for	Net energy (MJ/kg)	Lys.	Meth+ Cys[1]	Thr[2]	Trp.
piglets (8-25 kg)	9.67	10.0 **100**	5.9 **59**	5.7 **57**	1.9 **19**
starter pigs (25-45 kg)	9.49	9.0 **100**	5.3 **59**	5.1 **57**	1.7 **19**
growing pigs (45-70 kg)	9.23	7.5 **100**	4.5 **60**	4.4 **59**	1.4 **19**
finishing pigs (70-110 kg)	9.23	6.2 **100**	3.8 **61**	3.7 **60**	1.2 **19**
growing/finishing pigs (45-110 kg)	9.23	7.0 **100**	4.3 **61**	4.2 60	1.3 **19**

[1] Based upon methionine constituting 54% of the total content of ileal digestible sulfur containing amino acids; in the finishing feed 50% will be sufficient.

[2] No correction factor applied.

For entire males and fast growing females he recommended 10% higher amino acid levels (as g/kg diet). Also Baker (1996, 1997) adjusted his recommendations for SAA and threonine in a similar way (considering the effect of maintenance). Additionally, for apparent ileal digestible isoleucine Lenis and Van Diepen (1997) estimated the requirement of young growing pigs to be 57-60% of apparent ileal digestible lysine. The optimum ratio between essential amino acid N and total N for N utilization was between 0.45 and 0.55, depending on dietary protein level (Lenis et al., 1996; Lenis et al., 1999). The ratio is more important at lower protein levels. For N retention the optimum ratio was slightly lower. No positive effect could be shown of changing the composition of dietary non-essential amino acids (NEAA) on retention and utilization of N at a small reduction of protein level (Lenis, 1997). Therefore dietary NEAA composition in practice probably is adequate.

2) Phosphorus

Estimation of the exact requirement for minerals of pigs is a difficult task. Mostly two methods are used for this purpose: the empirical and the factorial approach, the latter being used more and more for macroelements (ARC, 1981; NRC, 1988; Jongbloed et al., 1994; Jongbloed et al., 1996b). The requirement for minerals depends on several factors, like animal (physiological status, production level and type of production), the diet and feeding strategy (amount of feed and chemical composition; chemical binding form and several interactions), and the criterium used (minimum or safe, and the evaluation method). This means that the estimated requirements can be diversified due to differences in assumptions. For scientific reasons the factorial approach is preferred, in which an estimate is given for maintenance and production. The estimate of the requirement for Ca can be derived from that of P. Based on literature data Jongbloed and Everts (1992) and Jongbloed et al. (1994) adopted a maintenance requirement for P of pigs of 6 $mg.kg\ LW^{-1}.day^{-1}$, being the difference between 9 and 3 $mg.kg\ LW^{-1}.day^{-1}$ when pigs are fed a sufficient and insufficient amount of P, respectively. In addition to the 6 $mg.kg\ LW^{-1}.day^{-1}$, 1 $mg.kg\ LW^{-1}.day^{-1}$ is adopted for endogenous loss of P in urine. In total 7 $mg.kg\ LW^{-1}.day^{-1}$ is used for endogenous loss for all categories of pigs. For estimation of the P requirement for growth (deposition of P in lean tissues and bones) an allometric function with a quadratic term for live weight (W) was used: $\ln P = 1.494 + 1.108 \ln W - 0.018 (\ln W)^2$.

With this equation the deposition of P per kg of growth in the traject from 5 to 110 kg LW can be calculated (figure 1). From Figure 1 it can be seen that the deposition of P per kg growth gradually decreases from 5.3 at 5 kg LW to 4.7 at 110 kg LW. Based on the starting points for maintenance and growth, Jongbloed et al. (1994) estimated for practice the requirement for digestible P of piglets (10-25 kg), starter pigs (25-45 kg), growing pigs (35-70 kg), and finishing pigs (70-110 kg) to be 3.4, 2.5, 2.1, and 1.7 g/EW (1 EW=12.6 MJ ME), respectively. For breeding sows, the requirement for P was 2.1 and 3.0 g digestible P/EW for pregnant and lactating sows, respectively. As we use a model, the recommended levels can be diversified according to level and type of production and physiological status of the animal.

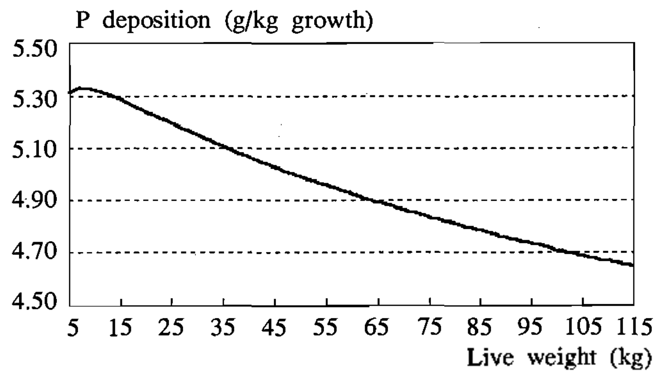

Figure 1. Course of P retention (g/kg weight increase) from 5 to 115 kg liveweight

As the required concentration of digestible AA and P per kg feed decreases as live weight (LW) of the pig increases, phase-feeding systems will help to tailor AAs and P in the diet better to the requirement of the animals (see chapter (Multi) phase feeding below).

3) Enhancement of digestibility of phosphorus and protein

In most raw materials of vegetal origin, P is stored in seeds both in organic and inorganic form. The organic part, a small part of which is in the form of phospholipids, consists mainly of phytate, the mixed calcium-magnesium-potassium salt of hexa-inositol phosphoric acid (phytic acid). Phytic acid readily forms complexes with several essential minerals, e.g., Ca, Zn, Mn, and Fe, and also protein (Nelson, 1967). The primary role of phytate in plant growth may be storage of P; the stored P is gradually utilized during seed germination (Williams, 1970). The phytate P can hardly be utilized by monogastrics because they lack an enzyme that can hydrolyze this molecule in the small intestine. There are some alkaline phosphatases that can hydrolyze phytate, but they seem to be of limited value for pigs. One should realize that not only phytic acid (IP6) may be present in the seeds, but also lower inositol phosphates, like penta-inositol phosphoric acid (IP5), and lower ones. These are especially present in technologically treated raw materials, like, maize gluten feed. Since a couple of years there are analytical procedures available that can analyse all kinds of inositol phosphates. The concentrations of total P and phytic acid P in some raw materials are listed in table 5.

The high excretion of P by pigs is mainly because about two-thirds of P in feedstuffs from plant origin is present as phytate. Phytate P is almost indigestible for pigs, which forces feed manufacturers and farmers to add inorganic P to their feeds. In the presence of supplementary or intrinsic phytase, phytic acid can be hydrolysed to liberate free orthophosphates and inositol for absorption (Pointillart, 1993). The first promising results by using genetically modified microbial phytase in pig and poultry feeds were reported by Simons et al. (1990). When 1000 units phytase/kg (1 unit = release of one μmol inorganic P per minute from an excess of sodium phytate at 37℃ and pH 5.5) were used, the digestibility of P increased from 27% to 51%. Studies with cannulated pigs indicated that the hydrolysis of phytic acid by microbial phytase occurred mainly in the stomach (Jongbloed et al., 1992). When 500 to 1000 units of Aspergillus niger phytase is added per kg of feed, the increase in amount of digestible P is almost 50% of the requirement for digestible P in a growing pig (Jongbloed et al., 1996a). Several types of microbial phytase have been found to enhance P digestibility substantially. Phytase-supplemented feeds for growing-finishing pigs and for pregnant sows may need little or no supplementary feed phosphate. Microbial phytase is commercially available now and has been incorporated in more than 70% of pig feeds in The Netherlands. More details on microbial phytase and its beneficial effects in pig feeding will be given in some chapters below.

Literature which shows a substantial enhancing effect of enzymes on protein/AAs digestibility in pigs is rather scarce, although recently some interesting results were presented (Liu et al., 1997). They found that the addition of ß-glucanase to hulless barley increased average ileal amino acid digestibility by 10%.

4) Changes in feedstuff composition

The wide variety of feedstuffs available for pig diets shows a considerable variation not only in P content but also in digestibility. Therefore, in order to decrease the excretion of P, feedstuffs should be chosen in which P is in a highly digestible form. Because feed phosphates are only used to supply P, one can easily choose those forms in which P is easily digestible. In The Netherlands, this has already led to an almost total shift to monocalcium phosphates at the expense of dicalcium phosphates.

Feedstuffs not only vary in N and AA content but also in AA content expressed per kg N. For economic reasons, it is impossible to formulate diets without oversupplying certain AAs, particularly when many by-products are used. Lowering the proportion of some by-products and other feedstuffs with a low ileal protein digestibility in the diet in favour of cereals and other feedstuffs with a higher protein digestibility will result in a better balance of dietary protein. Nitrogen excretion can also be substantially reduced by lowering the dietary protein level and supplementing the diet with lysine, methionine and, in most cases, threonine and tryptophan (see chapter The use of low protein, synthetic mino acids supplemented diets).

In addition to the changes mentioned before, there is also the possibility to enhance the energy concentration in the feeds. As a result mostly raw materials are chosen that have a higher digestibility, consequently leading to a lower excretion of N and minerals via faeces.

(MULTI) PHASE FEEDING

Both for AAs and P, the concentration per kilogram feed decreases as the live weight of the pig increases from 30 to 110 kg. Therefore, introduction of a two-, three- or multi-phase feeding will help balance AAs and digestible P 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) and Coppoolse et al. (1990). A slightly larger reduction in N and 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 computerized mechanical feeding system (Henry and Dourmad, 1993). A feeding strategy can be developed with a good fit of energy, protein and mineral supply based on pig potential, stage of production, production objective and environmental constraints. Bourdon et al. (1995) applied multi phase feeding to growing-finishing castrated male pigs between 25 and 100 kg live weight and decreased dietary protein levels, with supplementary addition of limiting amino acids, down to 13 and 10.7% in the multi phase diets A and B, respectively compared to a single control diet having 16.7% crude protein. From the experiments they calculated that the amount of excreted N was reduced by even 50% with 10% accounting for multi phase feeding. Van der Peet-Schwering et al. (1996) investigated multi phase feeding in growing-finishing female and castrated male pigs between 25 and 110 kg live weight in association with traditional and improved (low cost) housing system (a.o. slurry removal for lowering ammonia emission). By feeding 16.5 and 13.5% crude protein in the diets A and B, respectively compared to a single control diet containing 16% crude protein, they found a 15% reduction in N excretion and a 17% reduction in ammonia emission in the improved housing system. The combination of improved housing system and multi phase feeding reduced ammonia emission even by 45%! However some experiments in The Netherlands (Kemme et al., 1994) indicate the multi phase feeding not always leads to optimum performance and slaughter quality of the pigs. In the experiments of Van der Peet-Shwering (1996) the female multi phase fed pigs showed a less favourable feed conversion ratio and also in the research of Bourdon et al. (1995) there was a tendency for slightly decreased growth rate and increased backfat thickness of the multi phase fed pigs in the finishing period. Maybe some amino acid shortage in a part of the growing-finishing period or a less balanced energy-amino acid ratio in the diets are involved.

Concerning the reduction of P excretion by multi phase feeding, Beers et al. (1991) and Han et al. (1998) reported a 22% lower P excretion in growing-finishing pigs.

Required concentrations of N 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 N and P by 20% (Everts and Dekker, 1994).

THE USE OF LOW PROTEIN, SYNTHETIC AMINO ACIDS SUPPLEMENTED DIETS

The N excretion can be substantially lowered by reducing the protein level by more than 2%. In doing so, feeds need to be supplemented with lysine, methionine and, in most cases, also with threonine and tryptophan. Lenis et al. (1990) and Li et al. (1988) showed in their studies on fast-growing boars and gilts that dietary protein levels can be reduced by 2% without any disadvantageous effect on growth performance, when limiting AAs are supplemented sufficiently. The same was concluded by Fremaut and De Schrijver (1990) and Schutte et al. (1990) with young pigs. Lowering dietary crude protein level for growing-finishing pigs by 2% units will reduce N excretion by approximately 20%. This may be more than double the reduction observed for a 1% unit reduction in dietary protein because less digestible feedstuffs may be replaced for better digestible ones (Lenis, 1989). In a review of literature Kerr (1995) concluded that nitrogen excretion can be reduced by approximately 8.4% for each one percentage unit reduction in crude protein. Data from other experiments show that even larger reductions in dietary protein level are possible. Oldenburg and Heinrichs (1996) found no negative effect on performance and carcass leanness of reducing dietary protein levels from 17 to 13.5 % between 50 and 110 kg live weight. Also Quiniou et al. (1994), in experiments with growing pigs (30-100 kg) and lowering dietary protein level from 17.8 to 13.6%, did not find negative effects on performance and carcass characteristics. The N output was reduced by 33%. Bourdon et al. (1995), applying multi phase feeding at reduced crude protein levels, calculated a reduction of N excretion of even 50% in growing-finishing castrated male pigs between 25-100 kg live weight, compared to a single control diet having 16.7% crude protein. Very recently, Canh et al. (1998a) studying three diets with different crude protein levels (16.5, 14.5, and 12.5%), but similar contents of net energy and ileal digestible lysine, methionine + cystine, threonine and tryptophan in growing-finishing pigs, observed no significant effects of reduced protein levels on daily gain, feed intake, feed conversion ratio, and carcass yield. Also Tachibana (1998) did not find negative effects of a 4% dietary crude protein reduction in growing pigs. The reduction of urinary N excretion amounted 69%. Kerr et al. (1995), reducing dietary protein levels in starter, grower, and finisher diets from 19 to 15%, 16 to 12%, and 14 to 11% respectively, with or without supplementary amino acids, showed that the reduction in pig performance and carcass muscle that resulted from feeding reduced dietary crude protein levels could be corrected, provided that the proper amino acids were supplemented. In another experiment, however, Kerr and Easter (1995), when reducing dietary protein level fom 16 to 12% in pigs of about 22 kg, showed that maximal N retention was achieved only when the 12% crude protein diet was supplemented with both the deficient amino acids and a source of N for dispensable amino acid synthesis. In a performance study with growing-finishing pigs Cromwell et al. (1996) showed that pigs can perform optimally at a 4 percentage unit crude protein reduction with supplementary amino acids, but carcass leanness was reduced. Tuitoek et al. (1997) also found increased fat content in the carcass and increased backfat (and reduced ADG and feed efficiency) in pigs fed diets reduced by 4 percentage units of crude protein with synthetic amino acids (lysine, threonine, tryptophan, isoleucine, valine) added to meet an ideal amino acid ratio. Reduced gain, feed efficiency and increased fat content in the carcass also have been reported for pigs fed diets reduced by 5 percentage units of crude protein and supplemented with lysine, threonine, tryptophan, and methionine (Yu et al., 1991). However, Lopez et al. (1994) and Hahn et al. (1995) reported that pigs fed reduced crude protein (3.5 to 4%) diets supplemented with synthetic amino acids to meet an ideal amino acid ratio had similar carcass characteristics as pigs fed diets with a crude protein content at their requirement. Consequently, although several experiments show increased fatness traits of finishing pigs when feeding low crude protein, synthetic amino acids supplemented diets, the reports in literature are not consistent

So, it seems that there are still limitations to our knowledge of the optimum dietary amino acid pattern in pig diets, in particular in that for finishing pigs. Increased fatness may be also due to an increased net energy content of the low crude protein diets, because of a reduced energy need for deamination of excess amino acids. Thus more energy may be available in the low crude protein diets resulting in greater levels of fat deposition. In addition, pigs fed synthetic amino acid-supplemented diets have a reduced pancreas weight (Ward and Southern, 1995), which may indicate lower pancreatic activity and a lower energy requirement of these pigs, resulting in increased fatness. In some experiments also the energy evaluation system used (DE: digestible energy), may have resulted in a higher net energy level in the protein reduced diet because of underestimation of the (net) energy value of the ingredients of such a diet. These energy aspects stress the importance of using the net energy (NE) system.

Reducing dietary crude protein levels usually involves a reduction of the dietary level of soyabean meal in the diet. Because soyabean meal contains approximately 2.0 to 2.2% potassium, this will result in a significant decrease of the dietary potassium level and consequently in a lower potassium excretion. The lower dietary levels of protein and potassium may also lower ad libitum water intake of the pigs, which will reduce manure volume. Kay and Lee (1997) found an 11% decrease in slurry volume for each percent reduction of dietary crude protein.

THE EFFECT OF MICROBIAL PHYTASE ON THE DIGESTIBILITY/AVAILABILITY OF PHOSPHORUS AND CALCIUM

Effect on phosphorus digestibility

Since 1990, several experiments with exogenous microbial phytases were reported to quantify their effect on the apparent digestibility/availability of phosphorus. A survey of a large part of these studies has been presented by Jongbloed et al. (1996a), Düngelhoef and Rodehutscord (1995), Paik et al. (1996) and Weremko et al. (1997). One of the most interesting experiments was the dose-response effect of microbial phytase (Natuphos®) on the apparent digestibility of P investigated on growing pigs from 20 to 55 kg body weight (Beers and Jongbloed, 1992). Six doses of phytase (from 0 to 2000 $FTU.kg^{-1}$) were used in two types of grower diets (based either on corn-soybean meal or phytate-rich byproducts). The efficacy of microbial phytase appeared to be related to its dose and the type of diet (figure 2). For the corn-soybean meal based diet the relation could be illustrated by an exponential curve, with the following formula:

$$\text{digestible P } (g.kg^{-1}) = 1.86 - 0.9963^{dose},$$
$$R^2 = 96.7\%;\ \text{r.s.d.} = 0.067 \text{ g dig. P/kg.}$$

From 0 to 400 $FTU.kg^{-1}$ there was a rapid increase in microbial phytase efficacy, which was flattened afterwards. For the second type of diet, the response could be illustrated by a logistic curve, with the following formula:

$$\text{digestible P } (g.kg^{-1}) = 0.95 + 1.31/(1 + e^{(-5.51 \times 10\text{-}3(dose-377.8)}),$$
$$R^2 = 95.5\%$$
$$\text{r.s.d.} = 0.092 \text{ g dig. } P.kg^{-1}.$$

The conclusion of this experiment was that the efficacy of microbial phytase per FTU appeared to be the largest up to 500 FTU/kg diet. This dose was estimated to be equivalent to 0.8 g digestible P/kg diet.

Based on the curve for the corn-soybean meal based diet (figure 2) the responses of a large number of our own experiments have also been plotted. It showed that the response of the other experiments in our laboratory fit quite well with the curve for corn-soybean meal. In all experiments it is shown that microbial phytase is effective in enhancing P digestibility considerably and so increases the amount of digestible/available P in the feed for pigs.

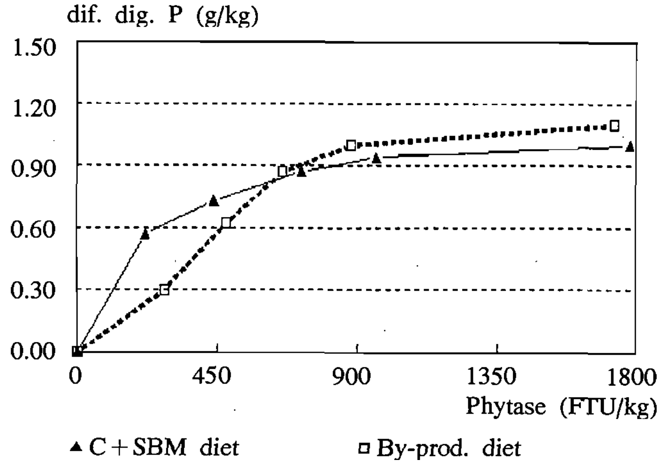

Figure 2. Improvement of digestible P by microbial phytase (Natuphos®) in two diets for growing pigs (Beers and Jongbloed, 1992)

The efficacy of microbial phytase also depends on animal related factors like physiological status and housing conditions (Kemme et al., 1997a). As mentioned before, Kemme et al. (1997b) showed that the efficacy of the phytase in generating digestible P decreased in the order of lactating sows, growing-finishing pigs, sows at the end of pregnancy, piglets, and sows at midpregnancy.

Effect on calcium digestibility

Phytate complexes may be formed with various di- and trivalent cations, as well as with protein (Wise, 1980). Microbial phytase supplementation results in increasing Ca digestibility of the feeds as well. To quantify this effect the ratio was calculated between the increase in amount of digestible Ca to the amount of digestible P. All available data from our own experiments and those of the literature were used. The ratios in our own experiments (n=12) were on average 0.55±0.19, while those from data in the literature (n=20) were significantly higher 0.84±0.33. We have no clear explanation for this difference, but the levels of dietary Ca and digestible P play certainly a part (Mroz et al., 1994b). In practical diet formulation the higher Ca digestibility means that supplementation of Ca in diets with microbial phytase can be slightly reduced, which may be beneficial due to the lower buffering capacity of the diet. By using 500 FTU/kg of feed, generating 0.8 g digestible P/kg and therefore between 0.4 and 0.7 g digestible $Ca.kg^{-1}$ is generated. Assuming a Ca digestibility of supplemental limestone of 60%, then between 1.7 and 3.0 g less $limestone.kg^{-1}$ of feed may be supplied.

Apart from its effect on P and Ca digestibility, phytase affects the availability of other minerals and nutrients. Microbial phytase can improve the apparent absorption of Mg, Zn, Cu and Fe (Jongbloed et al., 1996a). Besides, the observation by Guillot and Rambeck (1995) in rats, Japanese quails, and turkeys, that microbial phytase reduces cadmium accumulation in the liver and kidneys by 25 to 35% is also very interesting. This might be explained by the higher bioavailability of minerals and trace elements like calcium, zinc and iron, which are known to reduce the bioavailability of cadmium in different animal species.

PHYTASE AND ITS INTERACTION WITH PHYTIC ACID AND PROTEINS

Apart from binding mineral cations to the phytic acid molecule, phytic acid is also able to form complexes with protein and to inhibit or reduce α-amylase, trypsin, tyrosinase, and pepsin activities. According to Hartman (1979) 2 to 3% of a soy protein isolate is complexed with phytate. Such complexes might decrease the digestibility of proteins. Hydrolysis of phytic acid by phytases may not only increase the digestibility of P, but also the digestibilities of N and amino acids that are complexed with phytic acid.

Formation of complexes of phytic acid with proteins has been shown in several *in vitro* studies, and depends a.o. on the type of protein, the pH, and the level of calcium and magnesium (Jongbloed et al., 1997). However, it is very difficult to predict the magnitude of the complexing effect due to the complexity of the interactions.

Literature on the effect of microbial phytase on protein digestibility *in vivo* is limited and inconsistent. Maybe, the effect also depends on the concentration of phytate in the feed. Positive effects of phytase on protein digestibility may be explained by the following aspects:

a) the presence of native complexes of phytic acid and proteins in plant materials;
b) formation of complexes of phytic acid and proteins in the gastrointestinal tract of the pig;
c) formation of complexes of phytic acid with proteolytic enzymes in the gastrointestinal tract of the pig;
d) complexing of phytic acid to free amino acids.

To get more insight in the mechanism, and to explain differences in effect of addition of microbial phytase on protein digestibility, Jongbloed et al. (1997) performed several laboratory and animal studies at the ID-DLO. Only the aspect of c) together with the addition of phytase will be discussed here.

1) Effect of phytase on the binding between phytic acid and protein

Subsequently, the effect of phytase on the interaction between phytic acid and protein was studied. In this study, phytase was added prior and after precipitation of the complex. As could be expected, incubation of Na phytate with an excess of phytase before addition to the protein, prevented to a large extent the precipitation of protein both at pH 2 and 3. The amount of solubilised protein after addition of phytase and phytate was almost equal to the protein extract without any addition.

2) Effect of addition of phytase on the digestibility of protein

The next step was to study the effect of phytase on *in vitro* digestibility of protein. Therefore, the protein was incubated with pepsin at 37℃ under acid conditions (pH 2 and 3) during a time course of four hours. Incubation of the precipitate of protein and phytic acid was performed either in the presence of pepsin alone or with pepsin and phytase together. In the presence of phytase, the amount of précipitated protein was much faster reduced than with pepsin only (figure 3). Even at a ten times higher concentration of pepsin, addition of phytase had a beneficial effect. Similarly, with an increase in dissolved protein there was an increase of dissolved phytic acid. It was interesting to observe that, for the rapeseed meal, phytase was needed to dissolve protein from the precipitate, while pepsin only could not.

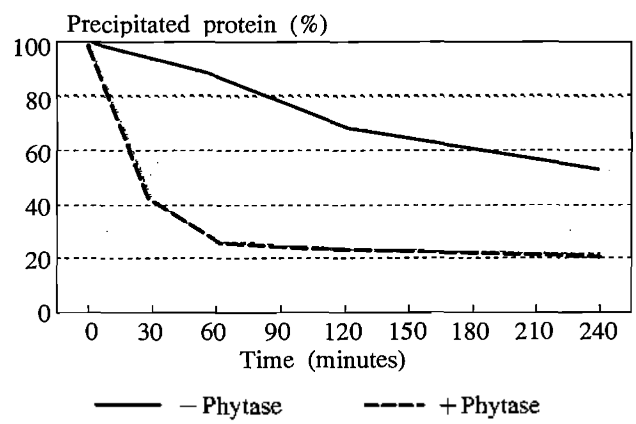

Figure 3. Effect of phytase on precipitated protein of soybean meal incubated with pepsin at pH2

From this in vitro research can be concluded that at pH 2 and 3 precipitation of protein and phytic acid at a ratio below 10 (g/g) takes place easily, and therefore protein escapes proteolytic hydrolysis. Adding microbial phytase can partly overcome this problem by dissolving protein from the precipitate. This effect depends on the feedstuff.

In vivo research at ID-DLO

As protein evaluation for pigs in The Netherlands is based on the apparent ileal digestibility (AID) of amino acids, we conducted two experiments in which a.o. the effect of microbial phytase on the AID of nitrogen and amino acids in pig diets has been investigated. Crude protein levels in the two diets were 170 g/kg and 130 g/kg, respectively. Further details of the experiments have been described by Mroz et al. (1994a) and Kemme et al. (1995).

In Experiment 1, a statistically significant effect of Natuphos® was obtained only on the AID of methionine and arginine, although the AID of CP, lysine, cystine, tryptophan, histidine and proline increased as well. Also, the AID of DM and OM were increased (table 9). Apparent total tract digestibility (ATTD) was significantly enhanced by microbial phytase, i.e., DM (1.8 %-units), OM (1.6 %-units), CP (2.3 %-units).

In Experiment 2, microbial phytase had a significant effect on the AID of CP and most of the amino acids (table 9; $p<0.05$ or $p<0.01$). In most cases they were 1 or 2 % units increased by microbial phytase. Only the cystine digestibility was slightly reduced. Microbial phytase had also a significant effect on the ATTD of DM and OM ($p<0.01$), and also tended to enhance the ATTD of CP ($p=0.056$).

Supplementation of feed phosphate had no effect on the AID of N, nor did affect the ATTD of DM, OM, and CP.

Table 9. *Apparent ileal digestibility (%) of dietary nutrients in relation to microbial phytase (main effects)*

	Experiment 1		Experiment 2	
Micr. phyt. (FTU/kg)	0	800	0	900
Dry matter	66.5	68.4	77.2	78.4
Organic matter	69.5	71.4	79.2	80.7
Crude protein	71.7	74.2	74.2^{c}	75.8^{d}
Lysine	81.0	81.9	77.5^{a}	79.9^{b}
Methionine	76.7^{a}	80.6^{b}	80.6	81.7
Cystine	70.5	74.1	73.4	73.0
Tryptophan	72.4	73.6	68.3^{a}	72.7^{b}
Isoleucine	80.1	79.8	77.9^{c}	80.0^{d}
Threonine	73.8	72.0	68.3^{c}	71.2^{d}

[abcd] Values within a row (for each experiment separately) lacking a common superscript differ significantly (a and b $p<0.01$; c and d $p<0.05$)

EFFECT OF MICROBIAL PHYTASE ON PIG PERFORMANCE

Jongbloed et al. (1996a) presented results on the effect of microbial phytase on performance of pigs. They compared the results, if possible, both with a negative control and a positive control treatment. However, the choice of a positive control treatment was not always evident. Therefore, they chose for the positive control a treatment with about 1 gram of supplementary P from a feed phosphate. However, in one half of the experiments the difference with the negative control treatment was often between 2 and 3 g of P. For their review, they chose 11 experiments where a reasonable comparison was possible. The relative values were calculated whereby those of the negative control diet were set on 100. The results are presented in table 10.

Data in table 10 show that the performance of both the positive control and the phytase groups were superior to the negative control group. The positive control group and the phytase supplemented group were almost identical. From the above mentioned experiments there were six experiments in which the positive control

Table 10. Relative performance of pigs using the negative control diet as 100 (n=11) and effect of phytase when added to the positive control diet (n=6)

	Negative control	Positive control	Effect phytase	Positive control	Effect phystase
Growth rate	100	115.0± 6.5	116.7± 10.6	100	106.0± 5.5
Feed intake	100	105.4± 5.2	107.6± 7.8	100	103.0± 3.2
FCR	100	93.0± 4.9	93.2± 5.0	100	95.7± 4.9

group was also supplemented with microbial phytase. Performance of the pigs receiving the positive control group with supplementary phytase was slightly better than those without phytase. The relative ratios compared with the positive control diet for growth rate, feed intake and feed conversion ratio were, 106.0±5.5, 103.0±3.2 and 95.7±4.9, respectively. This may imply that either the P requirement was not yet met, which is unlikely, or there is another positive effect of microbial phytase on performance.

Further calculations were performed on the effect of Natuphos® on the performance of piglets fed above their P requirement (Kies, 1997). Feed conversion ratio, corrected for differences in weight gain (25 g equals 0.01 unit FCR), was taken as the response variable. In total 11 experiments comprising 17 trials met his criteria. The experiments were analysed with the following model:

$$\text{Corrected FCR} = \text{Experiment}_i + b * \text{FTU/kg added;}$$

in which Experiment_i (i=1,17) is a constant per experiment, and b is the regression coefficient. The mean corrected FCR was 1.483. The value for b was -0.000094, with a 95% confidence interval of -0.000051 to -0.000136; R2 =0.94. It can be derived from the equation that dietary supplementation of 500 FTU Natuphos®/kg improves the corrected FCR with 0.047 units, which is close to the value reported by Jongbloed et al. (1996a). Due to lack of sufficient data he could only use a linear model, while it may be speculated that an exponential curve might be more physiologically appropriate. From the experiments of Campbell et al. (1995) and Selle et al. (1996) it can be concluded that also the dietary level of phytate is of influence on the improvement of the FCR.

The improvement of the FCR can be attributed to a higher digestibility of protein/amino acids and a slightly higher energy digestibility. Also, other unknown factors may play a part.

ENVIRONMENTAL IMPACT OF MICROBIAL PHYTASE

Without microbial phytase only approximately 20% of P in maize and 39% of P in soybean meal is digested by pigs. Because of the large amount of undigested dietary P, a substantial amount of P is excreted via faeces. Based on the estimates of Cromwell et al. (1993), the dose of microbial phytase equal to 1000 $FTU.kg^{-1}$ converted approximately one-third of the unavailable P to an available form. About 500 FTU/kg of diet generates approximately 0.8 g digestible $P.kg^{-1}$, which is equivalent to 1.0 g P from monocalcium phosphate or to 1.23 g P from dicalcium phosphate which is often used in the United States. This is illustrated in table 11. This table shows that with the supplementation of 500 $FTU.kg^{-1}$ of feed total P content is 1.3 $g.kg^{-1}$ lower. With the same performance as the control diet between 20 and 50 kg live weight and a feed conversion ratio in that traject of 2.5, it can be calculated that P excretion per kg growth is 4.75 instead of 8.0 g, which is 40% lower.

Table 11. Effect of microbial phytase (500 $FTU.kg^{-1}$ feed) on diet formulation and mineral content in a grower diet ($g.kg^{-1}$)

	P	Ca	Dig.P(%)	Feed-*	Feed+*
Corn	2.9	0.3	20	798.7	801.0
SBM dehulled	6.4	2.7	39	178.0	179.0
DCP.0 H_2O	200	250	64	8.5	2.3
Limestone	-	380	-	8.3	11.1
Salt+premix	-	-	-	6.5	6.5
Phytase premix	-	-	-	-	0.1
Total P	-	-	-	**5.2**	**3.9**
Dig. P	-	-	-	2.0	2.0
Ca	-	-	-	6.0	5.5

* -: without phytase; +: with phytase

CURRENT STATUS OF PHOSPHORUS AND NITROGEN EXCRETION BY PIGS IN THE NETHERLANDS, FRANCE AND DENMARK

In The Netherlands in a monitoring programme the concentrations of several minerals are occasionally monitored. Therefore, it is possible to estimate excretion of P by several categories of pigs. In table 12 a survey is presented for growing-finishing pigs from 1973 to 1996.

Table 12. Mean excretion of P and N of growing-finishing pigs from 25 to 110 kg in The Netherlands (kg/pig)

Year	In feed (g/kg)		Feed conversion ratio	Excretion	
	P	N		P	N
1973	7.4	23.8	3.37	1.62	4.74
1983	6.2	24.4	3.08	1.18	4.30
1988	6.0/5.0	26.9	2.94	0.85	4.64
1992	5.5/4.9	26.9	2.86	0.77	4.46
1994	5.3/4.6	26.6	2.76	0.68	4.16
1996	5.3/4.6	26.7	2.74	0.67	4.13

In that period performance increased considerably. In the live weight range of 25 to 110 kg growth rate increased from 625 to 737 $g.day^{-1}$, while feed conversion ratio improved from 3.37 to 2.74. Despite the better performance P content in pig diets decreased more than 2.5 $g.kg^{-1}$. The health of the pigs has not been impaired. From 1988 onwards it is common to feed a starter diet and a grower-finisher diet. Data in table 12 show that the excretion of P in growing-finishing pigs has more than halved in 20 years. With regard to N excretion only a slight decrease could be noted. The lower P excretion has, apart from increased nutritional knowledge, undoubtedly been stimulated by legislation based on P and by the use of microbial phytase. Microbial phytase is commercially available in The Netherlands since 1991 and is used in 70% of the pig feeds now. The incorporation levels of microbial phytase in pig diets will possibly further increase in the coming years, resulting in a further decrease of P excretion by pigs.

In table 13 data are presented on the output of manure by specific categories of pigs in France, Denmark and The Netherlands, as summarized by Jongbloed et al. (1998a).

In diets for slaughter pigs, N concentration is slightly lower while P content is substantially lower in The Netherlands than in the other two countries. Nitrogen excretion of slaughter pigs is substantially lower in Denmark than in the two other countries, while P excretion is lower in DK and NL than in F. Taking into consideration the differences in pig weight at slaughter, then the relative excretion (kg excreted/kg produced) is lowest in NL. Weaners have the lowest N and P excretion in The Netherlands. Sows in The Netherlands also excrete less N and P when compared with the other two countries.

REDUCTION OF AMMONIA EMISSION FROM PIGGERIES AND THE AMOUNT OF MANURE

In a preceding paragraph it was shown that Dutch legislation requires that NH_3 emission from livestock production has to be lowered substantially. For growing-finishing pigs, it means that the NH_3 emission per pig place has to be reduced from 2.10 (half-slatted floor) to 1.38 kg.

Ammonia emission from pig manure mainly originates 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. Due to the urease activity of faecal microbes, urea is rapidly converted into ammonia which easily volatilizes into the air. Factors influencing the rate of ammonia emission are concentrations of urea and ammonia/ammonium in the manure, temperature and air velocity, pH, emitting surface, and dry matter content (Aarnink et al., 1993a; Van Vuuren and Jongbloed, 1994).

It is possible to reduce ammonia emission substantially by nutrition management aimed at reducing the nitrogen and urea content in urine and slurry, lowering the pH of urine and slurry, and reducing total nitrogen excretion by improvement of the utilization of dietary protein. The latter reduces the amount of urea and N excretion. If with increased utilization of dietary protein the volume of the urine produced does not change, the concentration of mineral N in manure declines. This will result in a diminished emission of ammonia (Oldenburg and Heinrichs, 1996). However, to predict the amount of urine produced, quantitative insight is required with regard to factors that determine the water requirement. Besides, as a surplus of slurry on a farm often has to be transported over a long distance more attention should be paid to increasing DM content of slurry.

In order to reduce ammonia emission various techniques and feeding and housing measures have been developed by lowering dietary protein levels, changing the ratio between urinary N and faecal N (bacterially fermentable carbohydrates), reducing urea degradation (separation of urine and faeces, urease inhibitors), binding the ammonia (Yucca extract, clay minerals), lowering the slurry pH (acidification), and reducing the emitting surface (flushing, sloped floors, slurry removal; Van der Peet-Schwering et al. (1996) (see also chapter (Multi) phase feeding); Aarnink (1997)), airtight storage, soil injection). Some measures are costly, some are still speculative and need further research. The aim of feeding measures is to lower the concentration of urea and ammonia in the slurry and the pH of the slurry.

In recent years some research has been done on the

Table 13. Output of manure by specific categories of pigs in three European countries

	France (1996)		Denmark (1995)		The Netherlands (1995)	
	N	P	N	P	N	P
Slaughter pigs	28-108		30-100		26-113	
In diet (g/MJ ME)	2.03	0.46	2.03	0.42	1.98	0.36
Excretion (kg/pig)	4.12	0.91	3.38	0.72	4.26	0.73
Sows						
In diet (g/MJ ME)	1.95	0.46	1.88	0.49	1.86	0.40
Excretion (kg/year)	21.53	6.71	25.43	6.92	19.15	4.04
Weaners	8-28		7.5-30		7.5-26	
In diet (g/MJ ME)	2.19	0.51	2.19	0.54	2.05	0.39
Excretion (kg/pig)	0.59	0.15	0.67	0.19	0.38	0.06

relationship between nitrogen intake and ammonia emission. Latimier and Dourmad (1993) and Van der Peet-Schwering et al. (1996) fed pigs with a lower protein content. They found similarity in the relative reduction in nitrogen excretion in the urine and in ammonia emission. Aarnink et al. (1993b) estimated by model calculations a 9% reduction of ammonium N content in slurry when dietary crude protein is reduced by 10 g/kg. This was confirmed by a recent experiment of Canh et al. (1998a), studying the effect of three diets with different crude protein levels (16.5, 14.5, and 12.5%), supplemented with synthetic amino acids, on ammonia emission in both a balance and barn experiment with growing-finishing pigs. In the balance experiment ammonia emission was measured in vitro. Both balance and barn experiments showed similar effects of dietary CP on ammonia emission from slurry. Ammonia emission was reduced by 50% when dietary crude protein levels decreased from 16.5 to 12.5%, being 10-12.5% for each percent decrease in dietary CP. Sutton et al. (1998) found similar reductions in ammonium N and total N concentration of 28% when the crude protein level in a corn-soybean meal was reduced by 3% (from 13% to 10%) and supplementing the diet with synthetic amino acids. A reduction of the crude protein level from 18 to 10% with synthetic amino acids reduced ammonium N and total N in manure by 40% and 42%, respectively (Sutton et al., 1998). Reductions in ammonia emission are also in line with data from Kay and Lee (1997), who found reductions in ammonia emissions of 58% in growing and 46% in finishing pigs when the crude protein content of grower and finisher diet was reduced by 60 and 65 g/kg, respectively.

The study of Canh et al. (1998a) is one of few in which ammonia emissions were measured directly both in vitro and in a practical pig barn. It showed that ammonia emission measured in vitro gave a very good indication of the ammonia emission in the practical situation. In the study of Canh et al. (1998) dietary crude protein strongly influenced slurry pH, caused by the lower ammonium content of slurry from pigs fed a lower crude protein diet. On average, slurry pH decreased by 1 unit and 0.66 unit when dietary crude protein level decreased from 16.5% to 12.5% in the balance and barn experiment, respectively.

Concerning bacterially fermentable carbohydrates, several authors investigated possibilities to reduce the ratio between urinary N and faecal N by including these carbohydrates in the diet. Nitrogen incorporated in bacterial protein in faeces is less easily degraded to ammonia than urea-N excreted in urine. Microbial fermentation of OM in the hindgut can increase the excretion of N in faeces, while it reduces the N excretion in the urine. Recently Bakker et al. (1996) showed that inclusion of raw potato starch (PS), which is highly fermentable, in diets for growing pigs increased the amounts (g/d) of DM disappearing from the hindgut, while less N disappeared from the hindgut (table 14). With the diet PS there was even a net N appearence in the hindgut. The N excretion with urine was lower with more PS in the diets, while the N retention was not different.

Table 14. Nitrogen balance (relative values) and ammonia emission using fermentable carbohydrates

	Treatments		
	1	2	3
Intake	100	100	100
Feces	15	29	36
Urine	49	32	32
Retained	36	37	32
NH_3 emission	100	-	87

Treatment 1 : basal diet 35%, corn starch 65%
Treatment 2 : basal diet 35%, corn starch 32.5%, raw potato starch 32.5%
Treatment 3 : basal diet 35%, raw potato starch 65%

Different experiments were performed by Canh et al. (1996a, 1997a,b, 1998b) to influence the pH of faeces to lower the ammonia emission from pig manure. They found at larger proportions of non starch polysaccharides (NSP) in the diet of pigs, not only an altering in the N excretion pattern between urine and faeces (by which apparent N digestibility is negatively affected), but also a decrease of the pH of faeces and slurry. Slurry pH decreased with .12 unit and ammonia volatilisation by 5.1% for every 100 g/d extra intake of NSP (range NSP intake: 200-700 g/d; mean feed intake: 1.35 kg/d). Including sugar beet pulp (SBPS) in the diet of growing-finishing pigs at 0,5, 10 and 15% level (on DM basis) increased NSP content at each step by approximately 3%. The pH of slurry reduced by .4 to .5 unit and the ammonia emission by 14% for each 5% increase of SBPS. Also Sutton et al. (1997) found a significant reduction of the manure pH when 5% cellulose was added to the diet.

According to Canh et al. (1997a), a lower slurry pH related to a higher VFA content and a lower dietary base excess may also affect ammonia emission. Recently, Mroz et al. (1996) and Canh et al. (1997c) measured the effect of dietary cation anion difference (DCAD) and acidifying salts on urinary pH, nutrient retention and indoors ammonia emission by growing pigs (table 15). They added acidifying Ca-salts to dietary Ca levels of 7 and 10 g/kg. Urinary pH was reduced by 1.6 to 1.8 units, thereby diminishing ammonia emission by 26 to 53%. The highest ammonia reduction was for benzoate, which is metabolized to hippuric acid and excreted in the urine, causing a lower pH of the urine. Besides, reducing DCAD from 320 to 100 meq/kg DM lowered urinary pH by 0.48 units, and ammonia emission by 11%. In ruminants manipulating DCAD is much more difficult because of the higher basal cation-anion difference due to the high (mineral rich) grass consumption.

Hendriks et al. (1997) validated the experiment of Mroz et al. (1996) and Canh et al. (1997c) with growing and finishing pigs under practical conditions. The replacement of $CaCO_3$ in the diet by Ca-benzoate reduced the ammonia emission by 37%.

Table 15. Effect of dietary cation-anion difference (DCAD) and Ca source on urinary pH and ammonia emission

	DCAD (meq/kg DM)		Ca Source			
	320	100	CO_3	SO_4	Ben-zoate	Cl_2
pH Urine	7.34	6.75	7.05	5.44	5.25	5.39
NH_3 emission from manure, %	100	81	100	79	56	78

Concerning urease inhibitors, several dietary additives are claimed to increase nitrogen utilization, reduce urea degradation and reduce ammonia volatilization (Easter et al., 1993). Certain extracts of the Yucca plant are sometimes regarded as urease inhibitors, but their mode of action relies on binding or converting ammonia (Kemme et al., 1993b). Headon and Walsh (1994) reported promising effects of inclusion of these extracts in the diet of pigs in the USA, like a 50-70% reduction in ammonia concentration in the stable after 9 weeks. On the other hand, Kemme et al. (1993b) reported small and inconsistent reductions in ammonia emission after a two-week adaptation period at similar and higher dosages of Yucca extract. They concluded that for the Dutch practice inclusion in the diet will not provide a relevant contribution to ammonia reduction.

Results of inclusion of other materials, such as clinoptilolite and clay minerals on animal performance seem quite variable (maybe partly due to a lower dietary energy content), whereas their effect on ammonia emission is unclear (Easter et al., 1993; Krieger et al., 1993). However, recently we performed an experiment on growing pigs with a sepiolite at a 2% inclusion level in the diet and studied the effect on ammonia emission. A reduction of ammonia emission was measured by 6 to 7%, and approached significance (Canh et al., 1996b). It was calculated that almost all binding capacity of this material was used for binding the ammonia. Hornig et al. (1997) also obtained reduced ammonia emissions, when adding bentonite to the feed of growing pigs.

Concerning odor emissions, in 1995 the National Pork Producers Council (1995) (USA) stated that research correlating the effects of diet on odor from manures has been limited and concluded that introducing feed additives to bind ammonia and to bind or mask odor has met very little success and that more research work is needed to manipulate the diet altering microflora and enhancing metabolism in the lower gastrointestinal tract resulting in less precursors of odor causing compounds excreted.

It may be speculated that by reducing the ammonia emission also the amount of noxious odors will be reduced, allthough generally a poor relationship between ammonia emission and odor emission from pig houses is found. The latter seems to be caused by the different processes in the formation of ammonia and odor (Spoelstra, 1980). However, lowering dietary crude protein probably will reduce not only ammonia emission, but also odor emission (Aarnink et al., 1998). Aarnink et al. (1998) suggested to emphasize future research on reducing odor emissions on releaving the inhibition of methanogenesis in piggery wastes, which is an important cause of the accumulation of volatile odorous compounds in pig manure (Spoelstra, 1980). According to the latter author, inhibiting factors are: 1) low temperature of the manure; 2) overloading of the system, causing high concentrations of inhibiting components like hydrogen and ammonia; 3) toxic effects of heavy metals. The last two inhibiting factors can be influenced by dietary manipulation.

It may be concluded that the main possibilities at the moment to reduce the ammonia emission by feeding are: 1) lowering dietary protein content; 2) including additional NSPs in the diet and 3) adding acidifying calcium salts to the diet instead of $CaCO_3$ (Van der Peet-Schwering et al., 1997). Further research is needed, also to determine the dietary factors influencing the odor release from the manure.

IMPLICATIONS FOR PRACTICE

Dutch experiences learned that if environmental constraints can be anticipated at an early stage, less environmental problems due to animal husbandry might occur. Basically, the aim of governmental policy should be to achieve an equilibrium in fertilization, which means a good balance between input and output taking into account obligatory losses. Manure legislation can help to achieve this. However, farmers need time to adopt drastic measures and a socio-economic strong agriculture should still be possible. Besides, a regional approach can be recommended.

Nutrition management can substantially contribute to reduction in N and P excretion by pigs. Adequate knowledge is required on the digestibility of AAs and P in the feed used and on the requirement of these nutrients at any stage and type of production. Even more sophisticated evaluation systems than ileal digestible amino acids may be introduced (true digestible) in the future. 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. The use of enzymes for hydrolysing non-starch polysaccharides seems interesting. A powerful tool to decrease the excretion of N and P is to aim at improvements in feed conversion ratio of pigs. This also contributes to a lower excretion of minerals per kg lean meat, which probably can be considered as an even better criterion in judging excretion of pigs, because goal of pig production is to supply lean meat for the market. The incorporation of more synthetic AAs in the feeds and lowering crude protein content in the feed by 2% units can lower N excretion of growing pigs by 20%. Even bigger reductions in dietary protein level (up to 4%) might be possible, provided that the proper amino acids are supplemented. (Multi) phase feeding may reduce excretion of N and P with 10-15 and even 20%, respectively compared to a single control diet. However, multiphase feeding and big reductions in dietary protein level do not always lead to optimum performance and/or slaughter quality of the pigs, suggesting that some amino acid shortage in some period, probably the finishing, may occur. Therefore, special attention should be given to the accurate matching of supply and requirement of amino acids.

Research has learned that it is possible to reduce ammonia emission substantially by nutrition management using several measures. Some are still speculative and need further research. The main possibilities at this moment to reduce the ammonia emission by feeding are: 1) lowering dietary protein content; 2) including additional NSPs in the diet and 3) adding acidifying salts to the diet. Further research is needed, also for determining the dietary factors influencing the odor release from the manure.

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 genetical potential of the animals and hygienic conditions should be evaluated. An approach more at system level should be emphasized.

FUTURE OF PIG PRODUCTION FROM AN ENVIRONMENTAL VIEWPOINT

At the interface of sustainable agriculture and swine production Honeyman (1996) indicates four levels of issues, e.g. the farm, the rural community, the society or consuming public and the ecosystem or environment. It may be speculated that in the future pig production will have to deal with more constraints that are imposed from society. This may relate to animal well-being and health, quality of the animal product and production system, utilization of nutrients, and last but not least from an environmental viewpoint. Application of nutrients via manure and/or chemical fertilizers on the fields should be in close balance with the uptake by the crop, with minor losses via leaching or volatilization/evaporation.

To reduce or even eliminate exhaustion of gases and dust from pig operations, animals have to be kept in well insulated confinement systems. Therefore, vented air has to be cleaned before leaving the building, and cheap technological solutions are required. Furthermore, the expired CO_2 from the pigs can be re-used in greenhouses for vegetable production. Considering that more than one-half of the energy supplied to pigs is converted to heat, vented air may be re-utilized for heating (heat pump) the pig houses (in moderate climate zones) and/or for greenhouses. Also, better insulation of the building will result in using less fossil energy.

To reduce the surplus of minerals and N in a region, more recycling of kitchen wastes and of by-products from the food processing industry should be encouraged. Furthermore, development of technologies (enzymes, processing) to degrade fibrous raw materials may further enhance the utilization of energy from those raw materials in pig feeding. In certain regions manure processing (fermentation for methane production, manure separation, combustion) may be inevitable. The generated energy can be utilized on the farm or for the grid. In addition, the roof of the pig houses may also generate energy from photovoltage cells. By further integration in the whole production cycle, pig production can play an important link in the food production chain.

REFERENCES

Aarnink, A. J. A. 1997. Ammonia emission from houses for growing pigs as affected by pen design, indoor climate and behaviour. Ph. D thesis, Agricultural University, Wageningen, The Netherlands.

Aarnink, A. J. A., M. J. M. Wagemans, and A. Keen. 1993a. Factors affecting ammonia emission from housing for weaned piglets. In: M. W. A. Verstegen, L. A. den Hartog, G. J. M. van Kempen, and J. H. M. Metz (Eds.). Proceedings of the First International Symposium on Nitrogen Flow in Pig Production and Environmental Consequences. EAAP Publication no. 69. p 286-289. Pudoc, Wageningen, The Netherlands.

Aarnink, A. J. A., P. Hoeksma and E. N. J. Ouwerkerk. 1993b. Factors affecting ammonium concentration in slurry from fattening pigs. In: M. W. A. Verstegen, L. A. den Hartog, G. J. M. van Kempen, and J. H. M. Metz (Eds.). Proceedings of the First International Symposium on Nitrogen Flow in Pig Production and Environmental Consequences. EAAP Publication no. 69. p 413-420. Pudoc, Wageningen, The Netherlands.

Aarnink, A. J. A., A. L. Sutton, T.T. Canh, M. W. A. Verstegen and D. J. Langhout. 1998. Dietary factors affecting ammonia and odour release from pig manure. Paper Alltech Symposium, Lexington, Kentucky, USA, April 20-22, 1998, 14pp.

Agricultural Research Council, 1981. The Nutrient Requirements of Farm Livestock. no. 3. Pigs. Agricultural Research Council, London.

Baker, H., 1996. Advances in amino acid nutrition and metabolism of swine and poultry. In: Nutrient Management of Food Animals to Enhance and Protect the Environment, Kornegay, E.T., Ed., CRC Press, Inc., Boca Raton, New York, USA, 41.

Baker, H. 1997. Ideal amino acid profiles for swine and poultry and their applications in feed formulation. Kyowa Hakko Technical Review-9. Nutri-Quest Inc., Chesterfield, MO, U.S.A.

Baker, H. and Chung, T. K., 1992. Ileal protein for swine and poultry. Kyowa Hakko Technical Review-4. Nutri-Quest Inc., Chesterfield, MO, U.S.A.

Batterham, E. S., 1994. Protein and energy relationships for growing pigs. In: Principles of Pig Science, Cole, D. J. A., Wiseman, J. and Varley, M. A., Eds., University Press, Nottingham, U.K., 107.

Bakker, G. C. M., J. G. M. Bakker, R. A. Dekker, R. Jongbloed, H. Everts, J. van der Meulen, S. C. Ying, and N. P. Lenis. 1996. The quantitative relationship between absorption of nitrogen and starch from the hindgut of pigs. J. Anim. Sci., 74 (Suppl. 1), 188.

Beers, S., P.A. Kemme and C.M.C. van der Peet-Schwering. 1991. Effect of feeding method and decreased mineral content in the diet on mineral excretion and performance of growing pigs. Phase 1: Feeding to the estimated requirement of phosphorus with multi phase feeding (in Dutch), Report IVVO-DLO No. 231, Lelystad, The Netherlands.

Beers, S. and A. W. Jongbloed. 1992. Apparent overall (total tract) digestibility of P in relation to doses of Aspergillus niger phytase in diets for pigs. J. Anim. Sci. 70, suppl. 1:242.

Berschauer, F., 1990. Einfluss von B-Rezeptor-Agonisten auf den Protein- und Fettstoffwechsel, gbersichten zur Tierernährung, 18, 227.

Bourdon, D., J. Y. Dourmad and Y. Henry. 1995. Réduction des rejets azotés chez le porc en croissance par la mise en oevre de lalimentation multiphase, associée á labaissement du taux azoté, Journées Rech. Porcine en France, 27, 269.

Campbell, R.G., D. T. Harrison, K. J. Butler and P. H. Selle. 1995. Effects of dietary available phosphorus and phytase (Natuphos) on the performance of pigs from 19 to 40 days post-weaning. In: D.P. Hennessy and P.D. Cranwell (Eds), Manipulating pig production V, Proc. of the Fifth Biennial Conf. of the Australasian Pig Science Association, Werribee, Victoria, Australia, p. 193.

Canh, T. T., A. J. A. Aarnink, G. C. M. Bakker and M. W. A. Verstegen. 1996a. Effect of dietary fermentable carbohydrates on the pH of and the ammonia emission from slurry of growing-finishing pigs. J. Anim. Sci. 74 (Suppl. 1): 191 (Abstract).

Canh, T. T., A. W. Jongbloed, A. J. A. Aarnink, Z. Mroz, A. Alvarez, and F. Escribano. 1996b. Effect of sepiolite (Exal®) in diets of pigs on ammonia emission. In: Book of abstracts of the 47th Meeting of the European Association for Animal Production, Lillehammer, Norway, p. 242.

Canh, T. T., M. W. A. Verstegen, A. J. A. Aarnink, and J. W. Schrama. 1997a. Influence of dietary factors on nitrogen partitioning and composition of urine and feces of fattening pigs. J. Anim. Sci. 75:700-706.

Canh, T. T., A. J. A. Aarnink, J. W. Schrama and J. Haaksma. 1997b. Ammonia emission from pig houses affected by pressed sugar beet pulp silage in the diet of growing-finishing pigs. In: International Symposium on "Ammonia and Odour Control from Animal Production Facilities", (J. A. M. Voermans and G. J. Monteny, Eds), p. 273-281, Praktijkonderzoek Varkenshouderij, Rosmalen, The Netherlands.

Canh, T. T., A. J. A. Aarnink, Z. Mroz and A. W. Jongbloed. 1997c. Influence of dietary calcium salts and electrolyte balance on the urinary pH, slurry pH and ammonia volatilization from slurry of growing finishing pigs. J. Anim. Sci. 75 (Suppl. 1): 1989 (Abstract).

Canh, T. T., A. J. A. Aarnink, J. B. Schutte, A. Sutton, D. J. Langhout and M. W. A. Verstegen. 1998a. Dietary protein affects nitrogen excretion and ammonia emission from slurry of growing-finishing pigs. Submitted to Livestock Production Science.

Canh, T. T., A. L. Sutton, A. J. A. Aarnink, J. W. Schrama, M. W. A. Verstegen and G. C. M. Bakker. 1998b. Dietary carbohydrates alter fecal composition and pH and ammonia emission from slurry of growing pigs. Submitted to J. Anim. Sci.

C.B.S. 1995. Algemene milieustatistiek 1995, SDU uitgeverij, s'Gravenhage.

Coppoolse, J., A. M. van Vuuren, J. Huisman, W. M. M. A. Janssen, A. W. Jongbloed, N. P. Lenis and P. C. M. Simons. 1990. The excretion of nitrogen, phosphorus and potassium by farm animals, now and tomorrow (in Dutch), Dienst landbouwkundig Onderzoek, Wageningen, The Netherlands.

Corpen. 1996. Estimation des rejets dazote et de phosphore des élevages de porc. Ministère de lAgriculture et Ministère de lEnvironnement. 21 pp.

Cromwell, G.L., T. S. Stahly, R. D. Coffey, H. J. Monegue and J. H. Randolph. 1993. Efficacy of phytase in improving the bioavailability of phosphorus in soybean meal and corn-soybean meal diets for pigs. J. Anim. Sci. 71:1831-1840.

Cromwell, G. L., M. D. Lindemann, G. R. Parker, K. M. Lauren, R. D. Coffey, H. J. Moneque and J.R. Randolph. 1996. Low protein, amino acid supplemented diets for growing-fini-shing pigs, J. Anim. Sci., 74 (Suppl. 1), 174.

C.V.B. 1998. Table of Feedstuffs. Information about chemical composition, digestibility and feeding value (in Dutch), Centraal Veevoederbureau, Lelystad, The Netherlands

Dellaert, B. M., G. F. V. van der Peet, A. W. Jongbloed and S. Beers. 1990. A comparison of different techniques to assess the biological availability of feed phosphates in pig feeding, Neth. J. Agric. Sci., 38, 555-566.

D.L.G. 1987. Energie und Nährstoffbedarf landwirtschaftlicher Nutztiere. Nr. 4 Schweine. DLG Verlag Frankfurt (Main), Germany, 159 pp.

Düngelhoef, M. and M. Rodehutscord. 1995. Effects of phytases on the digestibility of phosphorus in pigs. Übers. Tierernährg. 23:133-157.

Easter, R. A., H. Stein, and N. L. Trottier. 1993. Use of biotechnology and feed additives. In: M. W. A. Verstegen, L. A. den Hartog, G. J. M. van Kempen, and J. H. M. Metz (Eds.). Proceedings of the First International Symposium on Nitrogen Flow in Pig Production and Environmental Consequences. EAAP Publication no. 69. p 169-172. Pudoc, Wageningen, The Netherlands.

European Union. 1991. Directive on protection of water quality.

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

Fremaut, D. and R. de Schrijver. 1990. Protein reduction in diets for growing-finishing pigs: Effects upon animal performance and nitrogen excretion (In Dutch), Landbouwtijdschrift, 43, 1007.

Fuller, M. F., R. MacWilliam, T.C. Wang and L.R. Giles. 1989. The optimum dietary amino acid pattern for growing pigs. 2. Requirements for maintenance and for tissue protein accretion, Br. J. Nutr., 62, 255.

Guéguen, L. 1977. A propos du contole de la qualité du phosphore des composés minéreaux. Elevage porcin 65:33-35.

Guillot, I. and W. A. Rambeck. 1995. Influence of feed enzyme phytase on cadmium accumulation in turkeys. In: W. van Hartingsveldt, M. Hessing, J. P. van der Lugt and W. A. C. Somers (Eds). Proceedings of Second Symposium on Feed Enzymes (ESFE2), Noordwijkerhout, The Netherlands, TNO Nutrition and Food Research Institute, Zeist, p. 301.

Han, In K., J. H. Kim, K. S. Chu, Z. N. Xuan, K. S. Sohn and M. K. Kim. 1998. Effect of phase feeding on the growth performance and nutrient utilization in finishing pigs. Asian-Aus. J. Anim. Sci. 11(5):558-565.

Hahn, J. D., R. R. Biehl and D. H. Baker. 1995. Ideal digestible lysine levelfor early- and late-finishing swine. J. Anim. Sci. 73: 773-784.

Hartman, G. H .J., 1979. Removal of phytate from soy protein. J. Amer. Oil Chemists' Soc. 56:731-735.

Headon, D. R., and G. Walsh. 1994. Biological control of pollutants. In: D. J. A. Cole, J. Wiseman, and M.A. Varley (Eds.). Principles of Pig Science. 375. University Press, Nottingham, U.K.

Hendriks, G. L., M. G. M. Vrielink and C. M. C. van der Peet-Schwering. 1997.Reducing ammonia emission from pig housing by adding acid salts to the feed. In: Proceedings of the Vth International Symposium on Livestock Environment (R. W. Bottcher and S. J. Hoff, Eds.), p. 65-70, ASAE, St. Joseph, Michigan, USA.

Henkens, Ch. H., 1975. Border between application and dumping of organic manure, Bedrijfsontwikkeling, 3: 343-347.

Henry, Y. and J. Y. Dourmad. 1993. Feeding strategy for minimizing nitrogen output in pigs. In: Proceedings of the First International Symposium on Nitrogen Flow in Pig Production and Environmental Consequences. M. W. A. Verstegen, L. A. Den Hartog, G. J. M. Van Kempen and J. H. M. Metz(Eds.), EAAP Publication no. 69, Wageningen, The Netherlands, 137.

Heij, G. J., and T. Schneider. 1995. Dutch priority programme on acidification. Final reportthird phase additional programme on acidification no. 300-15, RIVM, Bilthoven, The Netherlands.

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

Hornig, G., W. Berg and M. Turk, 1997. Harmful gas and odor emissions under use of feed and slurry additives. In: Proceedings of the Vth International Symposium on Livestock Environment (R. W. Bottcher and S. J. Hoff, Eds.), p. 78-85, ASAE, St. Joseph, Michigan, USA.

Huyghebaert, G., G. D. De Groote and L. Keppens. 1980. The relative biological availability of phosphorus in feed phosphates for broilers. Ann. Zootechn. 29: 245-263.

Jansman, A. J. M., W. Smink and P. van Leeuwen. 1997. Amount and amino acid composition of basal endogenous crude protein at the terminal ileum of pigs. Report ILOB-TNO I 96-31026c, Wageningen, The Netherlands.

Jensen, A.T., E. Jensen, V. Ravn and A. Unmack. 1977. Reactivity of inorganic feed additives. I. Dissolutionin vitro at pH 2.7 and 37oC of some oxides, carbonates and phosphates. Z. Tierphysiol. Tierernährg u. Futtermittelkunde 38:185-193.

Jondreville, C., J. van der Broeke, F. Gatel and S. van Cauwenberghe. 1995. Ileal digestibility of amino acids in feedstuffs for pigs. ITCF/Eurolysine publication, France, 52 pp.

Jongbloed, A. W. 1987. Phosphorus in the feeding of pigs; effect of diet on the absorption and retention of phosphorus by growing pigs, Ph.D thesis, Agricultural University, Wageningen, The Netherlands.

Jongbloed, A. W., 1992. Quantification of the efficacy of feed additives on the excretion of nitrogen and phosphorus, amount of manure and feed consumption of pigs (In Dutch), Mededelingen IVVO-DLO No. 17, Lelystad, The Netherlands.

Jongbloed, A.W., and P. A. Kemme. 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. and H. Everts. 1992. Apparent digestible phosphorus in the feeding of pigs in relation to availability, requirement and environment. 2. The requirement of digestible phosphorus for piglets, growing-finishing pigs and breeding sows. Neth. J. Agric. Sci., 40: 123-136.

Jongbloed, A. W., and N. P. Lenis. 1992. Alteration of nutrition as a means to reduce environmental pollution by pigs. Livestock Prod. Sci. 31:75-94.

Jongbloed, A. W., Z. Mroz and P. A. Kemme. 1992. 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, J. Anim. Sci., 70:1159-1168.

Jongbloed, A. W. and N. P. Lenis. 1993. Excretion of nitrogen and some minerals by livestock. In: Proceedings of the First International Symposium on Nitrogen Flow in Pig Production and Environmental Consequences.M. W. A. Verstegen, L. A. Den Hartog, G. J. M. Van Kempen and J. H. M. Metz (Eds), EAAP Publication no. 69, Wageningen, The Netherlands, 22.

Jongbloed, A. W., H. Everts, and P. A. Kemme. 1994. The requirement of digestible phosphorus for pigs (In Dutch), CVB-documentation report No. 10, Centraal Veevoederbureau, Lelystad, The Netherlands.

Jongbloed, A. W. and Ch. H. Henkens. 1996. Environmental Concerns of Using Animal Manure - The Dutch Case. In: E. T. Kornegay (Ed.). Nutrient Management of Food Animals to Enhance and Protect the Environment. p 315-333. CRC Press, Inc., Boca Raton, New York, USA.

Jongbloed, A. W., P. A. Kemme, and Z. Mroz. 1996a. Phytase in Swine Rations: Impact on Nutrition and Environment. In: BASF Technical Symposium. p 44-69. January 29, 1996, Des Moines, Iowa, BASF, Mount Olive, New Jersey, USA.

Jongbloed, A. W., J. D. Van der Klis, P. A. Kemme, H. A. J. Versteegh and Z Mroz. 1996b. Requirements for macroelements in pigs and poultry. A re-evaluation and a comparison between species. Paper EAAP-meeting, Lillehammer, Norway, 17 pp.

Jongbloed, A. W., L. H. De Jonge, P. A. Kemme and Z. Mroz. 1997. Phytates, Phytase, Phosphorus, Protein and Performance in Pigs. In: Proceedings BASF seminar, Canberra, Australia, 16 pp.

Jongbloed, A. W., H. D. Damgaard-Poulsen, J. Y. Dourmad and C. M. C. Van der Peet-Schwering. 1998. Environmental and legislative aspects of pig production in The Netherlands, France and Denmark. Livestock Production Science (submitted).

Kay, R. M. and P. A. Lee. 1997. Ammonia emission from pig buildings and characteristics of slurry produced by pigs offered low crude protein diets. In: International Symposium on "Ammonia and Odour Control from Animal Production Facilities", (J. A. M. Voermans and G. J. Monteny, Eds), p. 253-259, Praktijkonderzoek Varkenshouderij, Rosmalen, The Netherlands.

Kemme, P.A., A. W. Jongbloed, G. F. V. Van der Peet, B. M. Dellaert, S. Beers and R. A. Dekker. 1993a. [The digestibility of phosphorus in pig diets]. In: Stikstof en fosfor in de voeding van eenmagige landbouwhuisdieren in relatie tot de milieu-problematiek. Kwaliteitsreeks nr. 25, Productschap voor Veevoeder, Den Haag, Nederland.

Kemme, P. A., A. W. Jongbloed, B. M. Dellaert, and F. Krol-Kramer. 1993b. The use of a Yucca schidigera extract as "urease inhibitor" in pig slurry. In: M. W. A. Verstegen, L. A. den Hartog, G. J. M. van Kempen, and J. H. M. Metz (Eds.). Proceedings of the First International Symposium on Nitrogen Flow in Pig Production and Environmental Consequences. EAAP Publication no. 69. p 330-333. Pudoc, Wageningen, The Netherlands.

Kemme, P. A., N. P. Lenis, and C. M. C. van der Peet-Schwering. 1994. Effect of feeding method and decreased mineral content in the diet on mineral excretion and performance of growing pigs. Phase 2: Feeding to the estimated requirement of amino acids with multi phase feeding (in Dutch), Report ID-DLO No. 267, Lelystad, The Netherlands.

Kemme, P. A., A. W. Jongbloed, Z. Mroz and M. Mäkinen. 1995. Effect microbial phytase and phytate on ileal amino acid digestibility of a maize-soybean meal diet in pigs. In: 3. Tagung Schweine- und Geflügelernährung 29.11.-1.12.1994, Halle/Saale, 139-142.

Kemme, P. A., J. S. Radcliffe, A. W. Jongbloed and Z. Mroz. 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.

Kemme, P. A., A. W. Jongbloed, Z. Mroz and A. C. Beynen. 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.

Kerr, B. J. 1995. Nutritional strategies for waste reduction management: Nitrogen. In: J. B. Longenecker and J. W. Speers (Eds.). New horizons in animal nutrition and health. p. 47. The Institute of Nutrition, University of North Carolina, USA.

Kerr, B. J. and R. A. Easter. 1995. Effect of feeding reduced protein, amino acid-supplemented diets on nitrogen and energy balance in grower pigs, J. Anim. Sci., 73, 3000.

Kerr, B. J., F. K. McKeith and R. A. Easter. 1995. Effect on performance and carcass characteristics of nursery to finisher pigs fed reduced crude protein, amino acid-supplemented diets, J. Anim. Sci., 73, 433-440.

Kies, A.K., 1997. Niet-fosfor effecten van Natuphos® . In: BASF-symposium Enzymen en organische zuren in de Nederlandse mengvoederindustrie, Arnhem, March 19, 1997.

Krieger, R., J. Hartung, and A. Pfeiffer. 1993. Experiments with a feed additive to reduce ammonia emission from pig housing - preliminary results. In: M. W. A. Verstegen, L. A. den Hartog, G. J. M. van Kempen, and J. H. M. Metz (Eds.). Proceedings of the First International Symposium on Nitrogen Flow in Pig Production and Environmental Consequences. EAAP Publication no. 69. p 295-298. Pudoc, Wageningen, The Netherlands.

Kornegay, E.T. and J. S. Radcliffe. 1997. Relative bioavailability of phosphorus sources with different solubilities in neutral ammonium citrate (NAC) for young pigs. J.Anim. Sci. 75 (suppl. 1):188 (abstract)

Latimier, P. and J. Dourmad. 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: M. W. A. Verstegen, L. A. Den Hartog, G. J. M. Van Kempen and J. H. M. Metz (Eds.), Nitrogen Flow in Pig Production and Environmental Consequences. EAAP Publ. No. 69. Pudoc, Wageningen, The Netherlands, p. 242-246.

Leijen, C. G. J., J. Beukeboom, H. Jansen, and H Venneboer. 1993. Energy in intensive livestock farming. Publication IKC No. 39, Ede, The Netherlands.

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

Lenis, N. P. 1992. Digestible amino acids for pigs. Assessment of requirements on ileal digestible basis. Pig News Inf. 13:31N-39N.

Lenis, N. P. 1996. Requirements for apparent ileal digestible amino acids of growing pigs (in Dutch). In: CVB-Documentation Report No. 14:9-15. Centraal Veevoederbureau, Lelystad, The Netherlands.

Lenis, N. P., J. Th. M. van Diepen, and P. W. Goedhart. 1990. Amino acid requirements of pigs. 1. Requirements for methionine + cystine, threonine and tryptophan of fast-growing boars and gilts, fed ad libitum. Neth. J. Agric. Sci. 38:577-589.

Lenis, N. P., J. van der Meulen, J. Th. M. van Diepen, I. G. M. Bakker, and R. Jongbloed. 1996. Utilization of nitrogen and amino acids in growing pigs as affected by the ratio between essential and nonessential amino acids in the diet. J. Anim. Sci. 74 (Suppl. 1):172.

Lenis, N.P., J. Th. M. Van Diepen. 1997. Requirement for apparent ileal digestible isoleucine of young pigs. J. Anim. Sci 75 (Suppl. 1):185.

Lenis, N. P. 1997. Indispensable to dispensable amino acid ratios in swine. 14th BioKyowa Amino Acid Council Meeting, St. Louis, MO., USA, October 7-9, 35 pp.

Lenis, N. P., J. van der Meulen, J. Th. M. van Diepen, P. Bikker, and A. W. Jongbloed. 1999. Effect of the ratio between essential and nonessential amino acids in the diet on utilization of nitrogen and amino acids by growing pigs. J. Anim. Sci. (Accepted)

Li, D. F., W. T. Guan, H. M. Yu, J. H. Kim and In K. Han. 1998. Effects of Amino acid supplementation on growth performance for weanling, growing and finishing pigs. Asian-Aus. J. Anim. Sci. 11(1):21-29.

Liu, Y. G., S. K. Baidoo, and H. Schulze. 1997. Digestive responses of young pigs on microbial enzymes added to hulless barley diets: energy and amino acid digestibility. In: J. P. Laplace, C. Février and A. Barbeau (Eds). Proc. of the VIIth International Symposium on Digestive Physiology in Pigs, Saint Malo, France, EAAP Publication No. 88, p. 462-465.

Lopez, J., R. D. Goodband, G. L. Allee, G. W. Jesse, J. L. Nelssen, M. D. Tokach, D. Spiers and B. A. Becker. 1994. The effects of diets formulated on an ideal protein basis on growth performance, carcass characteristics, and thermal balance of finishing gilts housed in a hot, diurnal environment. J. Anim. Sci. 72: 367-379.

Lorimor, J. C., and S. W. Melvin. 1996. Animal manure recycle systems and its utilization in the USA. Proceedings 8th Animal Science Congress of the Asian-Australasian Association of Animal Production (AAAP), Chiba (Tokyo), Japan, Vol. 3, 13-20.

Mariscal-Landin, G. 1992. Facteurs de variation de lutilisation digestive des acides aminés chez le porc. Ph.D Thesis, Rennes University, France, 134 pp.

Moughan, P. J. and W.C. Smith. 1984. Assessment of a balance of dietary amino acids required to maximise protein utilisation in the growing pig (20-80 kg live weight), N. Z. J. Agric. Res., 27, 341.

Mroz, Z., A. W. Jongbloed and P. A. Kemme. 1994a. Apparent digestibility and retention of dietary nutrients bound to phytase complexes as influenced by microbial phytase and feeding regimen in pigs. J. Anim. Sci. 72:126-132.

Mroz, Z., A. W. Jongbloed and P. A. Kemme. 1994b. The influence of graded calcium supply on microbial phytase efficacy in starter diets for pigs. In: 45th Annual Meeting of the EAAP, Edinburgh, Scotland, paper P4.3.

Mroz, Z., A. W. Jongbloed, T. T. Canh, and N. P. Lenis. 1996. Lowering ammonia volatilization from pig excreta by manipulating dietary acid-base difference. Proceedings 8th Animal Science Congress of the Asian-Australasian Association of Animal Production (AAAP), Chiba (Tokyo), Japan, Vol. 2, 762-763.

National Pork Producers Council. 1995. A review of the literanure on the nature and control of odors from pork production facilities. J. R. Miner (Ed.) National Pork Producers Council, Des Moines, Iowa, USA.

Nelson, T. S. 1967. The utilization of phytate phosphorus by poultry. A review. Poultry Sci. 46: 862-871.

Noblet, J., J. Y. Dourmad and G. Dubois. 1993. The effect of porcine somatotropin and nitrogen losses in growing pigs. In: Proceedings of the First International Symposium on Nitrogen Flow in Pig Production and Environmental Consequences. M. W .A. Verstegen, L. A. Den Hartog, G. J. M. Van Kempen and J. H. M. Metz (Eds)., EAAP Publication no. 69, Wageningen, The Netherlands, 189.

NRC. 1988. Nutrient requirements of swine. N.A.S. Washington, D.C.: National Academic Press.

Oldenburg, J., and P. Heinrichs. 1996. Quantitative Aspecte einer proteinreduzierten Schweinemast. Lohmann Information 1:13-16.

Paik, I. K., R. Blair and J. Jacob. 1996. Strategies to reduce environmental pollution from animal manure: principles and nutritional management. a review. Asian-Aus. J. Anim. Sci. 9(6):615-635.

Pimentel, D., C. Harvey, P. Resosudarno, K. Sinclair, D. Kurz, M. McNair, S. Crist, L. Sphpritz, L. Fitton, R. Saffouri, and R. Blair. 1995. Environmental and economic costs of soil erosion and conservation benefits. Sci. 267:1117-1123.

Pointillart, A. 1993. Importance of phytates and cereal phytases in the feeding of pigs. In: C. Wenk, and M. Boessinger (Eds.). Enzymes in Animal Production. P 192-199. Kartause Ittingen, Switzerland.

Roland, D. A., R. W. Gordon, and S. K. Rao. 1993. Phosphorus solubilization and its effect on the environment. In: Proc. Maryland Nutr. Conf., 138-145. Departments of Poultry Science and Animal Sciences, University of Maryland, College Park, MD, USA.

Quiniou, N., J. Y. Dourmad, Y. Henry, D. Bourdon and D. Guillou. 1994. Influence du potentiel de croissance et du taux protéique du régime sur les performances et les rejets azotés des porcs en croissance-finition, alimentés á volonté, Journées Rech. Porcine en France, 26, 91.

Roth, F. X. and M. Kirchgessner. 1989. Influence of the methionine: cystine relationship in the feed on the performance of growing pigs. J. Anim. Physiol. Anim. Nutr., 61, 265.

Schutte, J.B., M.W. Bosch, N.P. Lenis, J. de Jong, and J.Th.M. van Diepen. 1990. Amino acid requirements of pigs. 2) Requirement for apparent digestible threonine of young pigs. Neth. J. Agric. Sci. 38, 597-608.

Selle, P. H., V. Ravindran, D. J. Cadogan, A. R. Walker and W. L. Bryden. 1996. The role of microbial phytases in poultry and pig production. Proc. Tenth Australian Poultry and Feed Convention, Melbourne, Australia, p. 219-224.

Sheen, S. Y and C. M. Hong. 1998. Disposal of animal waste: the magnitude of the problem in Asia and Australasia. Proceedings Pre-Conference Symposia of the 8th World Conference on Animal Production, June 28 July 4, 1998, Seoul National University, Seoul, Korea, 376-385.

Simons, P. C. M, H. A. J. Versteegh, A. W. Jongbloed, P. A. Kemme, P. Slump, K. D. Bos, M. G. E. Wolters, R. F. Beudeker and G. J. Verschoor. 1990. Improvement of phosphorus availability by microbial phytase in broilers and pigs. Br. J. Nutr. 64: 525.

Spoelstra, S.F. 1980. Origin of objectionable odorous components in piggery wastes and the possibility of applying indicator components for studying odour development. Agric. Environ. 5: 241-260.

Sutton, A. L., K. B. Kephart, J. A. Patterson, R. Mumma, D. T. Kelly, E. Bogus, B. S. Don, D. D. Jones and A. Heber. 1997. Dietary manipulation to reduce ammonia and odorous compounds in excreta and anaerobic manure storage. In: International Symposium on "Ammonia and Odour Control from Animal Production Facilities", (J. A. M. Voermans and G. J. Monteny, Eds), p. 245-252, Praktijkonderzoek Varkenshouderij, Rosmalen, The Netherlands.

Tachibana, F., and H. Ubugai. 1998. Effect of reducing crude protein and energy content in diets with amino acid supplementation on nitrogen balance, performance and carcass characteristics in pigs. Jap. J. of Swine Sci. (submitted).

Tuitoek, K., L. G. Young, C. F. M. de Lange and B. J. Kerr. 1997. The effect of reducing excess dietary amino acids on growing-finishing pig performance: An evaluation of the ideal protein concept. Journal of Animal Science 75, 1575-1583.

Van Boheemen, P. J. M., M. E. Berghs, F. R. Goosensen, P. Hotsma, and P. C. Meeuwissen. 1991. Environmental pollution in 2000 by application of K. In: H. A. C. Verkerk (Editor). Manure and environment in 2000. Scope from agricultural research. p 61-71. DLO, Wageningen, The Netherlands.

Van der Peet-Schwering, C. M. C., N. Verdoes, M. P. Voermans, and G. M. Beelen. 1996. Effect of feeding and housing on the ammonia emission of growing and finishing pig facilities (in Dutch), Report Experimental Pig Station No. P 1.145, Rosmalen, The Netherlands.

Van der Peet-Schwering, C. M. C., A. W. Jongbloed and A. J. A. Aarnink. 1997. Nitrogen and phosphorus consumption, utilization and losses in pig production. The situation in The Netherlands. Paper P2.5, 48th Annual Meeting of the European Association for Animal Production, Vienna, Austria, 18pp.

Van Erp, P. J., and P. van Lune. 1991. Long-term heavy-metal leaching from soils, sewage sludge and soil/sewage sludge mixtures. In: P. L?Hermite (Editor). Treatment and use of sewage sludge and liquid agricultural wastes. p. 122-127. Elsevier Applied Science, London.

Van Rhee, J. A. 1974. I.C.W. Report on regional studies No. 6:18, Wageningen, The Netherlands.

Van Vuuren, A. M., and A. W. Jongbloed. 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.

Wang, T. C. and M. F. Fuller. 1989. The optimum dietary amino acid pattern for growing pigs. 1. Experiments by amino acid deletion. Br. J. Nutr., 62, 77.

Ward, T. L. and L. L. Southern. 1995. Sorghum amino acid-supplemented diets for the 50- to 100-kilogram pig. J. Anim. Sci. 73: 1746-1753.

Watanabe, S. 1996. Animal production environment: present situation and issues. Proceedings 8th Animal Science Congress of the Asian-Australasian Association of Animal Production (AAAP), Chiba (Tokyo), Japan, Vol. 1, 75-82.

Weremko, D., H. Fandrejewski, T. Zebrowska, In K. Han, J. H. Kim and W. T. Cho. 1997. Bioavailability of phosphorus in feeds of plant origin for pigs. a review. Asian-Aus. J. Anim. Sci. 10(6):541-550.

Wicke, G. 1972. Prüfung von neuen Futterphosphaten auf ihre P-verfügbarkeit für Broiler, Schweinen und Lämmer. 4. Prüfung verschiedener Futterphosphate bei wachsende Schweinen. Arch. Tierernährung 22: 163-174.

Wise, A. 1980. Dietary factors determining the biological activities of phytate. Nutr. Abstr. Rev. 53:791-806.

Williams, S. G., 1970. The role of phytic acid in the wheat grain. Plant Physiol. 45: 376-381.

Yano, F., T. Nakajima, and M. Matsuda. 1998. Reduction of nitrogen and phosphorus from livestock waste: a major priority for intensive animal production. Proceedings Pre-Conference Symposia of the 8th World Conference on Animal Production, June 28 July 4, 1998, Seoul National University, Seoul, Korea, 469-477.

Yu, I. T. , H. T. Yen and J. F. Wu. 1991. Amino acid additions to low-protein corn-soybean meal diets for growing pigs. J. Agr. Assn. China. 154: 94-100.