9 Feeding Systems for Pigs

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INTRODUCTION

In commercial pig production, the main objective of diet formulation and feeding strategy is to maximize profits, which does not necessarily imply maximal animal performance. To maximize the economic efficiency, therefore, supplying indispensable nutrients as close as possible to meeting, but not exceeding, the requirements of the pig is advantageous. Such optimum feeding strategies involve consideration of a multitude of factors such as genetic variations in the pig (sex and genotypes), alternative feed ingredients, variability, availability and stability of nutrients in feed ingredients, interactions among the nutrients and non-nutritive factors, voluntary feed intake, physical and social environment, and others. In addition, there must be an effective means to incorporate all the necessary information to formulate efficient diets in a convenient and economical manner. Because of declining profit margins in recent years, offering diets containing just enough nutrients to satisfy the needs of the pig would have a significant impact on the profitability and success of the pig enterprise. Furthermore, it will have a positive impact on today's environmentally conscious society by reducing the excretion of unutilized nutrients.

It is reasonable to assume that pigs with different sex and genotypes can express their genetic potential for growth, production and/or reproduction if they are provided with the opportunity to consume the optimum amounts of all nutrients in just the proportions required to satisfy their needs. Vitamins and minerals are obviously important nutrients for pigs to perform optimally, but their requirements can be met with relatively little cost. On the other hand, amino acids and energy together account for more than 90% of total feed costs (SCA, 1987). From a practical standpoint, the efficient utilization of these nutrients is essential for economical production of animal products. In this chapter, therefore, emphasis will be placed on energy and protein or amino

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acid nutrition, although brief discussions on minerals and vitamins are included. As for arguably the most critical nutrient, water, and its closely related area of electrolytes and/or electrolyte balance, the readers are referred to excellent reviews on the subjects including those by Brooks and Carpenter (1993), Frazer *et al.* (1993) and Patience (1993).

Although the nutrient requirements of pigs have been published by several organizations in various countries including Australia, France, Germany and The Netherlands, the most well established are those of the UK's Agricultural Research Council and the USA's National Research Council (Lewis, 1991). The nutrient requirements established by those two organizations are, therefore, included in this chapter. Extensive reviews on establishing the nutrient requirements, factors influencing the requirement and satisfying the needs and other pertinent topics in pig nutrition have been presented by ARC (1981), SCA (1987), NRC (1988), Whittemore (1993) and others, including many excellent articles in books edited by Cole and Haresign (1985), Miller *et al.* (1991) and Cole *et al.* (1993).

In this chapter, the discussion will be limited to some areas that the author feels pertinent to feeding the pig satisfactorily. The nutrient requirements established by the NRC (1988) and ARC (1981) are discussed first, with the emphasis on energy and amino acids. In the subsequent sections, the estimation of the requirements and satisfying the nutrient needs are discussed, followed by discussion on some factors that can have a great impact on the nutrient requirements and satisfying the needs of the pig. A brief discussion on pig wastes and environment is also included.

ENERGY REQUIREMENTS OF GROWING PIGS AND SOWS

Energy Systems

Defining the energy requirement and energy content of feedstuffs in terms of digestible energy (DE), rather than gross energy (GE), enhances the accuracy of diet formulation because the variation in digestibility is the major factor affecting the efficiency of energy utilization from various feed sources. Metabolizable energy (ME) takes into account the energy lost in the urine and combustible gases produced in the digestive tract. Net energy (NE) is the difference between ME and heat increment. Because it is the energy ultimately required by the animal for maintenance or production, the NE would be the best measure of the energy that is available to the animal. The estimation of the NE is, however, difficult and imprecise and affected by many factors (NRC, 1988). Therefore, the use of NE might be too sensitive to be of practical use (Wiseman and Cole, 1985) and unlikely to provide any greater precision in formulating diets or predicting responses compared with the ME or DE system (Whittemore, 1993).

The amount of energy lost in the urine is not a constant, and the ME content of the diet decreases with poor quality and excess protein relative to the pig's needs because of the increased excretion of nitrogen (N) as urea

(Filmer and Curran, 1985). The following equation (NRC, 1979) can be used to take into account the quantity of crude protein (CP):

$$ME = DE\ [96 - (0.202\%\ CP)]/100 \qquad (9.1)$$

Other equations describing the relationship between the ME and DE have been reported by ARC (1981). The published ME to DE ratios range from 0.92 to 0.98 (ARC, 1981; Filmer and Curran, 1985; NRC, 1988). For practical purposes, a commonly accepted value of 0.96 is regarded as an appropriate factor for a wide range of ingredients and diets. The loss of energy as combustible gases in pigs is generally ignored because the losses are negligible and difficult to measure (NRC, 1988). Furthermore, the variation in the relationship between DE and ME is more of a function of the animal than of the feed ingredient itself (Whittemore, 1993). In addition, DE values for the pig are available for most of the commonly used feed ingredients. For these reasons, it is preferable to use DE values, which can be determined much more easily and precisely, rather than the ME, to express the requirements of pigs and describe the energy value of feed ingredients and diets.

Requirements of Growing Pigs and Sows

Growing pigs

The DE requirements of the growing pig can be estimated by a factorial approach, and the following equation can be used for that purpose:

$$DE = DE_m + DE_{pr} + DE_{fr} + DEH_c \qquad (9.2)$$

where DE_m, DE_{pr}, DE_{fr} and DEH_c are the requirements for maintenance, protein retention, fat retention and cold thermogenesis, respectively (NRC, 1988). Similarly, ARC (1981) placed an emphasis on the factorial approach, but they also used an empirical method in their estimation of the requirements. In addition, the use of the factorial approach was extended to allow prediction of basic performance responses to be assessed against existing empirical observations (Close and Fowler, 1985).

The energy requirement for maintenance is usually expressed as a function of body weight to the power of 0.75, though other exponents may be more appropriate (Whittemore, 1993). Many factors can influence the energy needs for maintenance, but most of the estimated DE_m requirements fall between 0.418 and 0.523 MJ kg body weight $(BW)^{-0.75}$ day^{-1}, with the mean of 0.460 (NRC, 1988). Estimates for the energy costs of protein accretion range from 29.7 to 61.1 MJ of DE kg^{-1} with an average of 52.7, whereas the estimates for fat accretion range from 39.7 to 68.2 MJ of DE kg^{-1} with an average of 52.3 (Tess *et al*., 1984). Lean muscle tissues, however, contain only 20–22% protein, thus the energy cost per unit of lean muscle is considerably less than that for fat accretion (NRC, 1988). On the other hand, the energy lost as heat in protein turnover may reduce the efficiency of protein accretion as compared with fat accretion. The energetic efficiencies of protein and fat accretion have been reported to be 0.54 and 0.74, respectively, with corresponding estimated DE requirements of 45.7 MJ kg^{-1} for protein and 55.7 MJ kg^{-1} for fat accretion (ARC, 1981).

The estimates of DE requirements for maintenance and growth apply to pigs kept in thermoneutral conditions, and less energy would be available for growth when ambient temperature (T) falls below the critical temperature (T_c). The lower and upper critical temperatures can be defined as the temperatures below and above ambient temperatures where energy must be used to maintain optimum body temperature. The energy cost of cold thermogenesis can be derived from the following equation:

$$DEH_c \text{ (kJ of DE day}^{-1}) = (1.365 \text{ BW} + 98.96)\ (T_c - T) \qquad (9.3)$$

where BW is in kg and T_c and T are expressed in degrees Celsius (ARC, 1981). Assuming a partial efficiency of energy utilization below T_c to be 0.8, the increase in energy requirements can be estimated (ARC, 1981). The estimates of DE requirements for maintenance and daily DE intake of growing pigs are presented in Tables 9.1 and 9.2, respectively.

Pregnant and lactating sows

The factorial approach to estimate the energy requirements of the sow during pregnancy has been summarized by NRC (1988). An energy intake during gestation is generally restricted to control weight gain and maintain appropriate condition of the sow, because the greater the weight gain during pregnancy, the greater the weight loss during lactation (ARC, 1981). The DE_m requirements have been estimated to be 0.402–0.699 MJ with a mean of 0.460 MJ kg $BW^{-0.75}$ day^{-1}, whereas the DE requirement for maternal protein and fat gain is

Table 9.1. Estimates of digestible energy for maintenance (DE_m) based on the two equations using different exponents of live weight ($BW^{0.63}$ or $BW^{0.75}$)[a,b].

	DE_m (MJ day^{-1})	
Live weight (kg)	$BW^{0.63}$	$BW^{0.75}$
5	2.06	1.59
10	3.20	2.69
20	4.95	4.51
30	6.39	6.11
40	7.66	7.58
50	8.80	8.97
60	9.88	10.28
70	10.89	11.54
80	11.84	12.76
90	12.75	13.94

[a]Based on ARC (1981) and Close and Fowler (1985).
[b]Estimates derived from the equation $DE_m = 0.749\ BW^{0.63}$, and the estimates from the same data if the equation is constrained to the exponent of 0.75 ($DE_m = 0.477\ BW^{0.75}$, where BW = live weight in kg).

Table 9.2. Daily digestible energy (DE) intake of the growing pig (MJ day^{-1}).

		ARC[a]	
Body weight (kg)	NRC[b]	4 × M[c]	Asymptotic[d]
1–5	3.6		
5–10	6.5		
10–20	13.5		
20–50	27.0		
50–110	44.2		
20		19.8	18.4
30		25.5	25.1
40		30.6	30.6
50		35.2	35.2
60		39.5	38.8
70		43.6	41.8
80		47.4	44.2
90		51.0	46.2

[a]ARC (1981).
[b]NRC (1988).
[c]Daily DE intake based on 4 × maintenance (M) requirement, where maintenance (MJ) = 0.749 $BW^{0.63}$ and BW = live weight in kg.
[d]Daily DE intake based on an asymptotic equation, DE (MJ) = $55(1 - e^{-0.0204BW})$.

assumed to be 52.3 MJ kg^{-1} gain. If the composition of maternal gains consists of about 25% fat and 15% protein, the energy cost of maternal gain can be calculated as 20.9 MJ of DE kg^{-1}. With a desirable net weight gain of 25 kg during pregnancy, the daily DE requirement is 4.60 MJ. The daily energy requirement for uterine gain has been estimated to be 0.79 MJ of DE, thus the daily DE requirement during gestation is 5.40 MJ. Assuming an energetic efficiency of 0.80, the DE_m requirement would be increased by 19.8 kJ kg $BW^{-0.75}$ for each 1°C decrease in temperature below the T_c (Close and Fowler, 1985).

The estimates of the energy requirements during lactation have been based on the requirement for maintenance, milk production and the contribution from the mobilization of tissue resulting from the inevitable loss of body weight (Close and Fowler, 1985; Noblet *et al*., 1990). The DE_m has been reported to be 0.460 MJ kg $BW^{-0.75}$ day^{-1}, but it may be 5–10% greater than that reported for the pregnant sow (NRC, 1988). The energy requirement for milk production is 8.4 MJ of DE kg^{-1} milk based on the GE content of 5.4 MJ of DE kg^{-1} milk and an efficiency of utilization of 65% (Close and Fowler, 1985). The contribution derived from body weight is assumed to represent the loss of lipids (Close and Fowler, 1985). Based on the conversion of body fat to milk fat, which has an energy value of 41.0 MJ of DE kg^{-1} fat with the conversion efficiency of 0.85, body weight loss can contribute 48.7 MJ of DE kg^{-1} (ARC, 1981).

Daily DE requirements of both pregnant gilts and sows and lactating sows are presented in Table 9.3. It has been demonstrated that additional feed during late gestation (Cromwell *et al*., 1989) and supplementation of the diets with lipids during late gestation or lactation (Moser and Lewis, 1980) can improve the reproductive performance of the sow. Depending on their cost-effectiveness, therefore, these management practices may be beneficial in increasing the sow productivity.

Table 9.3. Daily digestible energy (DE) requirements of pregnant and lactating sows.

Class and body weight (kg)	NRC[b]	ARC[a]	
		Low/medium[c]	High[d]
Pregnant gilts and sows[e]			
142.5	24.4		
162.5[f]	26.3		
182.5	28.3		
120		25.5	29.8
140		27.6	31.9
160		29.7	33.9
Lactating sows[g]			
145	60.7		
165	73.2		
185	85.8		
140		62.8	71.2
160		64.8	73.2
180		66.8	75.1
200		68.6	77.0

[a]ARC (1981).
[b]NRC (1988).
[c]Based on the requirements for pregnant gilts and sows on a net gain of 20 kg during pregnancy (low), whereas the requirements for lactating sows are based on medium milk yield (medium; 6.25 kg day^{-1}).
[d]Based on the requirements for pregnant gilts and sows on a net gain of 40 kg during pregnancy (high), whereas the requirements for lactating sows are based on high milk yield (high; 7.25 kg day^{-1}).
[e]Based on the NRC requirements for a 25 kg maternal weight gain and 20 kg conceptus gain, and the weights indicated are mean gestation weights; for the ARC, feed intake should be increased by between 3 and 4% per 1°C decrease in temperature.
[f]The same DE requirement for adult boars (162.5 kg) as the requirement for a 162.5 kg sow.
[g]For the NRC, based on the requirements for the assumed milk yield of 5.0, 6.25 and 7.5 kg day^{-1} for 145, 165 and 185 kg sows, respectively; for the ARC, based on the requirements indicated for a 21 day weaning.

PROTEIN AND AMINO ACID REQUIREMENTS

Protein and Non-protein Nitrogen

The difference between crude and true protein, and the role of non-protein nitrogen (NPN) in pig nutrition have been reviewed by Lewis (1991). The use of a single factor (6.25) to convert N to protein works well in expressing the protein content of feed ingredients or diets because typical diets contain mixtures of protein and mean N contents that are usually close to 16%. Similarly, most of the NPN in many feed ingredients is in the form of amino acids, which can be utilized efficiently by pigs. In general, therefore, the use of crude protein (CP) values is sufficiently accurate for most instances in pig nutrition.

To be of nutritional value, NPN must be in a form that can be converted to protein within the pig. Pigs are capable of absorbing amino acids synthesized from NPN by intestinal bacteria (Niiyama *et al*., 1979), and can incorporate them into tissue proteins (Grimson et al., 1971). These results indicate that pigs have the ability to utilize inexpensive NPN sources, and overall utilization of diets may be improved by the inclusion of NPN (Chiba *et al*., 1995). However, it is generally assumed that the amount of NPN utilized by pigs would be too small to elicit substantial beneficial effects on the performance because of their anatomical and metabolic limitations (NRC, 1976).

Protein Quality and Amino Acid Balance

The body uses mixtures of amino acids collectively for protein synthesis, thus the balance of amino acids is very important for an optimum utilization of protein (Whittemore, 1993). Any departure from a desirable pattern of amino acids may lead to a reduction in pig performance, at least in terms of the efficiency of protein utilization (Lewis, 1991). In addition, it may result in acute neurological aberrations and even death (D'Mello, 1994). The topic of amino acid disproportions, imbalance, antagonism and toxicity, has been reviewed in detail by Harper *et al*. (1970). Adverse effects of the imbalance and antagonism can be alleviated by supplying the limiting amino acid(s) and structurally related amino acid(s), respectively. Amino acid toxicity is not likely to be a problem in practical pig nutrition, and it is usually associated with errors in formulation and/or mixing of diets using crystalline amino acids.

Ideal protein

Proteins serve to supply each individual indispensable amino acid and an adequate amount of dispensable amino N as a whole to meet the needs of the animal. Ideal protein can be described operationally as protein that cannot be improved by any substitution of a quantity of one amino acid for the same quantity of another (Fuller and Chamberlain, 1985); it has been derived from individual estimates of amino acid requirements, the composition of sow's milk and body tissues (Lewis, 1991), and the results of experiments designed specifically for that purpose (Wang and Fuller, 1989). The ARC (1981) adopted the ideal protein concept in their estimation of the amino acid requirements for growing pigs. On a practical basis, the proportions of threonine, tryptophan and methionine + cysteine relative to lysine are perhaps the most important because these amino acids are likely to be limiting after lysine (Knabe, 1996).

In general, pigs seem to be able to tolerate quite wide variations in the pattern of amino acids, provided all the indispensable amino acid requirements are satisfied (Lewis, 1991). Furthermore, excess or moderate oversupply of some individual amino acids is unlikely to have clear adverse effects on the performance of pigs, as mentioned by Chiba *et al.* (1991a). Nevertheless, consideration of the ideal protein concept in diet formulation would be beneficial in terms of efficient utilization of dietary amino acids. The patterns of amino acids in ideal protein for growing pigs proposed by various research groups are summarized in Table 9.4.

Requirements of Growing Pigs and Sows

The subject of dispensable, indispensable and conditionally dispensable amino acids has been reviewed by Lewis (1991) and Fuller (1994). Pigs do not have a requirement for protein as such, but they need adequate amounts of indispensable amino acids and a sufficient amount of non-specific N in the diet to synthesize dispensable amino acids. It is generally assumed that if the indispensable amino acid supply is adequate for pigs fed a conventional diet, then the amount of dispensable amino acids would be sufficient. With increased use of crystalline amino acids, however, this assumption may not be valid. Sufficient amounts of both fractions must be provided in the diet to support an optimum performance of pigs.

Table 9.4. Proportions of each amino acid in ideal protein relative to lysine.

Amino acid	Cole (1978)	ARC (1981)	NRC (1988)[a]	Wang and Fuller (1989)	Chung and Baker (1992)[b]
Lysine	100	100	100	100	100
Arginine	—	—	43	—	42
Histidine	40	33	26	—	32
Isoleucine	50	55	54	60	60
Leucine	100	100	71	111	100
Methionine + cysteine	50	50	49	63	60
Phenylalanine + tyrosine	100	96	79	120	95
Threonine	60	60	57	72	65
Tryptophan	18	15	14	18	18
Valine	70	70	57	75	68

[a]Based on lysine:tryptophan and arginine:tryptophan ratios of 7.0 and 3.0, respectively.
[b]The proportions of amino acids for pigs weighing 5–20 kg.

The NRC (1988) amino acid requirements have been derived from the results of various experiments designed for that purpose, and certain theoretical principles of amino acid nutrition have been considered in the process. A summary of extensive reviews on research designed to establish each amino acid requirement of growing pigs and gestating and lactating sows has been presented by the NRC (1988).

Growing pigs

Fuller and Chamberlain (1985) summarized the factorial and empirical approaches used by the ARC (1981) in establishing the protein requirements of growing pigs. The ARC (1981) indispensable amino acid recommendations are expressed in terms of their relationships to the lysine content of ideal protein, and they assumed that such an ideal balance is equally applicable for pigs from birth to 90 kg. Similarly, the NRC (1988) assumed that the proportion of amino acids required is relatively consistent throughout the growth phases.

The amino acid requirements of growing pigs established by the ARC (1981) and NRC (1988) are presented in the Table 9.5. An adequate amino acid intake, along with other indispensable nutrients, is necessary to maximize lean accretion in growing pigs. Therefore, making appropriate adjustments according to various factors, some of which will be discussed later, is very important in establishing the allowances for a population of pigs.

Table 9.5. Amino acid requirements of very young and growing pigs (g kg^{-1}).

	Pig weight (kg) or age (weeks)								
	NRC (1988)					ARC (1981)[a]			
Amino acid	1–5	5–10	10–20	20–50	50–110	0–3[b]	3–8[b]	15–50	50–90
Lysine	14.0	11.5	9.5	7.5	6.0	15.8	13.8	11.0	7.8
Arginine	6.0	5.0	4.0	2.5	1.0	—	—	—	—
Histidine	3.6	3.1	2.5	2.2	1.8	5.2	4.5	3.6	2.6
Isoleucine	7.6	6.5	5.3	4.6	3.8	8.6	7.5	6.0	4.3
Leucine	10.0	8.5	7.0	6.0	5.0	15.8	13.8	11.0	7.8
Methionine + cysteine	6.8	5.8	4.8	4.1	3.4	7.9	6.9	5.5	3.9
Phenylalanine + tyrosine	11.0	9.4	7.7	6.6	5.5	15.1	13.3	10.4	7.5
Threonine	8.0	6.8	5.6	4.8	4.0	9.4	8.3	6.5	4.7
Tryptophan	2.0	1.7	1.4	1.2	1.0	2.3	2.0	1.6	1.2
Valine	8.0	6.8	5.6	4.8	4.0	11.0	9.7	7.7	5.5

[a]Based on the requirements for pigs weighing 15–90 kg on the assumption that the diet contains 13.0 MJ kg^{-1}.
[b]Age in weeks; based on the requirements on the assumption that the diet contains 14.1 MJ kg^{-1}, which is similar to the energy density recommended by the NRC (1988) for young pigs.

Pregnant and lactating sows

The NRC (1988) requirements for pregnant gilts and sows have been estimated experimentally, or based on the amount needed for satisfactory N retention during the late phase of pregnancy. Similarly, the requirements for lactating sows have been estimated experimentally or extrapolated from the published requirements for maintenance and the amount needed to support milk production. Although the ARC (1981) indicated that the evidence is insufficient to test the validity of using ideal protein concept for adults, they expressed the amino acid requirements in terms of a balance relative to lysine along with daily intake of amino acids and dietary percentages. The patterns of amino acids for pregnant and lactating sows proposed by several research groups have been summarized by Fuller (1994).

The amino acid requirements of sows established by the ARC (1981) and NRC (1988) are presented in the Table 9.6. Several researchers (Stahly *et al*., 1990; Johnston *et al*., 1993) reported that sows producing large amounts of milk and nursing large litters responded to higher amino acid levels than those recommended by the NRC (1988). Sow productivity has increased in recent years for various reasons (Knabe *et al*., 1996). It is important, therefore, to consider the genetic potential of lactating sows, as well as other factors, in establishing the allowances.

Table 9.6. Amino acid requirements of pregnant gilts and sows and lactating sows (g kg^{-1}).

	Pregnancy[a]		Lactation[b]	
Amino acid	NRC[c]	ARC[d]	NRC[c]	ARC[d]
Lysine	4.3	4.3	6.0	6.3
Arginine	0.0	—	4.0	4.2
Histidine	1.5	1.3	2.5	2.5
Isoleucine	3.0	3.7	3.9	4.4
Leucine	3.0	3.2	4.8	7.2
Methionine + cysteine	2.3	2.9	3.6	3.4
Phenylalanine + tyrosine	4.5	3.3	7.0	7.2
Threonine	3.0	3.6	4.3	4.4
Tryptophan	0.9	0.7	1.2	1.2
Valine	3.2	4.6	6.0	4.4

[a]Based on the requirements of feed intakes of 1.9 kg (or 26 MJ of DE) and 2.0 kg day^{-1} (or 25 MJ of DE day^{-1}) for the NRC and ARC, respectively.
[b]Based on the requirements of feed intakes of 5.3 kg (or 74 MJ of DE) and 5.25 kg day^{-1} (or 66 MJ of DE day^{-1}) for the NRC and ARC, respectively.
[c]NRC (1988).
[d]ARC (1981).

MINERAL AND VITAMIN REQUIREMENTS

Mineral Requirements

The importance of mineral elements for normal life processes was recognized even in ancient times. Minerals have extremely diverse functions, including their roles in skeletal structure, homeostasis, cell membranes, enzymes and hormones. Pigs require at least 13 known mineral elements including calcium, chlorine, copper, iodine, iron, magnesium, manganese, phosphorus, potassium, selenium, sodium, sulphur and zinc (NRC, 1988). Cobalt is also required for the synthesis of vitamin B_{12}, but there is no convincing evidence that non-ruminant species need this element with adequate vitamin B_{12} in the diet. Pigs may also need other elements such as arsenic, boron, bromine, cadmium, chromium, fluorine, lead, lithium, molybdenum, nickel, silicon, tin and vanadium, but these elements are required at such low levels that their dietary essentiality has not been proven (NRC, 1988).

Based on the corn–soybean meal diet formulated to satisfy the lysine requirement of a 25 kg pig (NRC, 1988), corn and soybean meal can supply only few minerals in adequate amounts to satisfy the needs, and others are clearly deficient or marginal at best. In recent years, a supplementation of diets with pharmacological levels of zinc (2500–3000 p.p.m.) has been shown to enhance growth performance and reduce scouring of weanling pigs (Hahn and Baker, 1993; Poulsen, 1995), even though, there are some conflicting results (e.g. Schell and Kornegay, 1994). Similarly, the beneficial effects of chromium supplementation on the carcass quality of grower–finisher pigs (Page *et al*., 1993a; Lindemann *et al*., 1995) and the reproductive performance of sows (Lindemann *et al*., 1995) have been reported. Several minerals are toxic at very low concentrations, and the toxicity and tolerance of those mineral elements have been reviewed by the NRC (1980).

Vitamin Requirements

Vitamins constitute only a small fraction of the diet but they are important in the health, well-being and productivity of the animal. The fat-soluble vitamins include vitamins A, D, E and K, whereas water-soluble vitamins include thiamin, riboflavin, niacin, vitamin B_6, pantothenic acid, biotin, folacin, vitamin B_{12}, choline and ascorbic acid. The water-soluble vitamins are relatively non-toxic, but excesses of dietary vitamin A and D have been shown to cause some toxic effects (NRC, 1987). Pigs fed chemically defined diets have a dietary requirement for all of the fat- and water-soluble vitamins except ascorbic acid.

As with the minerals, the corn–soybean meal diet formulated to satisfy the lysine requirement of a 25 kg pig (NRC, 1988) can supply only few vitamins in adequate amounts. It is generally assumed that feed ingredients and microbial synthesis in the gastrointestinal tract are adequate to satisfy the requirements for vitamin B_6, thiamin, folic acid and biotin, but the beneficial effects of biotin supplementation on reproductive performance of sows have been reported over the years (Kornegay, 1986). In addition, folic acid supplementation is likely to improve litter size, especially among sows with a high ovulation rate, as Lindemann (1993) concluded in his review. Similarly, although further research is needed, there might be an opportunity to increase the reproductive performance of sows by short-term administration of β-carotene or vitamin A at critical stages of the reproductive process (Brief and Chew, 1985; Coffey and Britt, 1992).

The mineral and vitamin requirements are presented in Tables 9.7 and 9.8, respectively. Recent findings on beneficial effects of minerals may indicate that some mineral elements play a critical role(s) in not only achieving acceptable pig performance, but realizing the full genetic potential for growth, production and/or reproduction. A similar conclusion can be drawn for some vitamins. Further research is needed to elucidate fully the effect of those nutrients on the performance of pigs and the economical feasibility of using those nutrients.

ESTABLISHING AND SATISFYING THE NUTRIENT REQUIREMENTS

Comparison of the NRC and ARC Requirements

The similarities and differences between the NRC (1979) and ARC (1981) in estimating the energy and protein requirements of growing pigs have been reviewed by Lewis (1993). Although there were some differences, the approaches used by the NRC (1988) in their latest revision and the ARC (1981) in arriving at the recommendations seem to be very similar. The revised nutrient requirements of the NRC (1988) and those recommended by the ARC (1981), however, indicate the differences in the final estimation for some nutrients. Although the estimates of amino acid requirements for sows during gestation and lactation are quite similar, there are clearly large differences in the estimates for growing pigs, with the ARC values being greater for all stages (Lewis, 1991). The NRC (1988) requirements are based on gilts and castrates fed *ad libitum*, whereas the ARC (1981) requirements are based on both *ad libitum* and restricted feeding regimens, and include boars, which may partly account for the differences as mentioned by Chiba (1989). It is not reasonable to assume that there are such large differences in the requirements of pigs, indicating a need for further research in this area of establishing nutrient requirements (Lewis, 1991).

Establishing the Nutrient Requirements

Empirical and factorial approaches

In this section, the discussion on the estimation of the requirements is generally limited to protein or amino acids, but, to a large extent, the general premises presented here would be equally applicable to other nutrients. Nutrient requirements can be determined by the empirical and/or factorial

Table 9.7. Mineral requirements of growing pigs, and pregnant and lactating sows.

	Pig weight (kg) or class											
	NRC[a]							ARC[b]				
Mineral (U kg^{-1})	1–5	5–10	10–20	20–50	50–110	Pregnancy	Lactation	Up to 20	20–55[c,d]	55–90	Up to 90	Sows
Calcium (g)	9.0	8.0	7.0	6.0	5.0	7.5	7.5	9.9	8.1	7.2	—	8.1
Phosphorus (g)	7.0	6.5	6.0	5.0	4.0	6.0	6.0	8.1	6.3	5.4	—	6.3
Available phosphorus (g)	5.5	4.0	3.2	2.3	1.5	3.5	3.5	—	—	—	—	—
Sodium (g)	1.0	1.0	1.0	1.0	1.0	1.5	2.0	—	1.2	—	—	—
Chlorine (g)	0.8	0.8	0.8	0.8	0.8	1.2	1.6	—	1.4	—	—	—
Magnesium (g)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	—	—	—
Potassium (g)	3.0	2.8	2.6	2.3	1.7	2.0	2.0	2.3	2.3	—	—	—
Copper (mg)	6.0	6.0	5.0	4.0	3.0	5.0	5.0	—	—	—	3.6	—
Iodine (mg)	0.14	0.14	0.14	0.14	0.14	0.14	0.14	—	—	—	0.14	0.45
Iron (mg)	100	100	80	60	40	80	80	54	—	—	—	—
Manganese (mg)	4.0	4.0	3.0	2.0	2.0	10.0	10.0	—	—	—	4–14	9.0
Selenium (mg)	0.3	0.3	0.25	0.15	0.10	0.15	0.15	—	—	—	0.14	—
Zinc (mg)	100	100	80	60	50	50	50	—	—	—	45	—

[a]NRC (1988); based on the requirements of feed intakes of 1.9 kg (or 26 MJ of DE) and 5.3 kg day^{-1} (or 74 MJ of DE day^{-1}) for pregnant and lactating sows, respectively.
[b]ARC (1981); converted to 'air dry' basis (900 g kg^{-1} dry matter).
[c]For chlorine and sodium, the requirements for pigs weighing 20–35 kg.
[d]For potassium and magnesium, the requirements for pigs weighing up to 45 and 55 kg, respectively.

Table 9.8. Vitamin requirements of growing pigs, and pregnant and lactating sows.

	Pig weight (kg) or class											
	NRC[a]							ARC[b]				
Vitamin (U kg^{-1})[c]	1–5	5–10	10–20	20–50	50–110	Pregnancy	Lactation	Up to 20[d]	Up to 40[e]	20–90[f]	Up to 90	Sows
Vitamin A (IU)	2200	2200	1750	1300	1300	4000	2000	—	1800	1200	—	2100
Vitamin D (IU)	220	220	200	150	150	200	200	126	—	108	—	—
Vitamin E (IU)	16	16	11	11	11	22	22	10.7	—	6.7	—	8.1
Vitamin K (mg)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	—	0.27	—	—	—
Biotin (mg)	0.08	0.05	0.05	0.05	0.05	0.20	0.20	—	—	—	—	—
Choline (g)	0.6	0.5	0.4	0.3	0.3	1.25	1.00	0.71	—	< 0.9	—	0.9–1.7
Folacin (mg)	0.3	0.3	0.3	0.3	0.3	0.30	0.30	—	—	—	—	—
Niacin (mg)	20.0	15.0	12.5	10.0	7.0	10.0	10.0	18.0	—	12.6	—	—
Pantothenic acid (mg)	12.0	10.0	9.0	8.0	7.0	12.0	12.0	—	—	—	9.0	9.0
Riboflavin (mg)	4.0	3.5	3.0	2.5	2.0	3.75	3.75	—	—	—	2.3	2.7
Thiamin (mg)	1.5	1.0	1.0	1.0	1.0	1.0	1.0	—	—	—	1.4	—
Vitamin B_6 (mg)	2.0	1.5	1.5	1.0	1.0	1.0	1.0	—	—	—	2.3	1.4
Vitamin B_{12} (μg)	20.0	17.5	15.0	10.0	5.0	15.0	15.0	16.2	—	9.0	—	13.5

[a]NRC (1988); based on the requirements of feed intakes of 1.9 kg (or 26 MJ of DE) and 5.3 kg day^{-1} (or 74 MJ of DE day^{-1}) for pregnant and lactating sows, respectively.
[b]ARC (1981); Converted to 'air dry' basis (900 g kg^{-1} dry matter).
[c]For the ARC estimates, assumed 1 IU of vitamin A, D and E = 0.30 μg of retinol, 0.025 μg of vitamin D_3 and 0.67 mg of D-α-tocopherol, respectively.
[d]For niacin, the requirement for pigs weighing up to 10 kg.
[e]For vitamin K, the requirement for pigs weighing up to 30 kg.
[f]For niacin and vitamin A, the requirements are for pigs weighing between 10 and 70 kg and between 40 and 90 kg, respectively.

method, both of which are considered by the ARC (1981) and NRC (1988). The empirical method involves the evaluation of the responses of pigs to different concentrations or intakes, and the requirement is the concentration or intake up to which there is a favourable response and beyond which there is no further response. There are many difficulties associated with this method including: (i) observation of diminishing marginal responses without defining clearly a point of maximum response; (ii) the difference in the estimates depending on the criterion of response used; and (iii) the effect of many factors such as some aspects of the diet, animal or environment on the response pattern (ARC, 1981; Whittemore, 1993). The requirements estimated by the empirical method, therefore, may have limited usefulness because the results may be applicable to the specific conditions under which the experiment was conducted (Knabe, 1996).

The factorial method, in its simplest form, assumes that the requirement is the sum of the requirements for maintenance, tissue protein accretion and/or milk protein secretion, with some considerations for the efficiency of protein or amino acid utilization (Fuller and Chamberlain, 1985). Unlike the empirical method, this approach is more flexible, and takes into account various factors that can affect the requirements (Knabe, 1996) and allows requirements to be estimated for animals differing in their productive state (Fuller, 1994). However, present knowledge of the factors contributing to protein requirements is little more than rudimentary (Fuller and Chamberlain, 1985). For instance, one of the limitations in the application of this approach is a paucity of information on the efficiency of amino acid utilization for various components constituting the requirements (Fuller, 1994). There is, therefore, nearly as much empiricism in the factorial method as in the empirical method (Fuller and Chamberlain, 1985). The accuracy of the projected requirements depends on the validity of the data used in the estimation, and many assumptions themselves may need verification.

Modelling approach as an alternative

Estimating the nutrient requirements with accuracy and precision is rather difficult because a multitude of factors can affect the requirements, implying that no single set of estimates would satisfy the nutrient requirements of all animals. Although not complete, the published information necessary to formulate effective diets for pigs and to establish their likely responses to changes in dietary or environmental conditions seems to be available. However, the interactions among many factors that determine growth and productivity make it difficult to apply all the information in practice (SCA, 1987), and a modelling approach might be the only defensible means of incorporating all the necessary information (Ferguson *et al.*, 1994). Several pig simulation models have been developed and/or described in detail, including those by Black *et al.* (1986), SCA (1987), Pettigrew *et al.* (1992), Whittemore (1993) and Ferguson *et al.* (1994); see Chapter 16 of this book.

As indicated by Whittemore (1993), the main purpose of a model is to show the direction and magnitude of the response and the sensitivity of the production system to a tactical or strategic change so that more effective financial and management decisions can be made. This implies that it is not necessary for a model to come to a single optimum solution. Instead, it would be better to provide the options and guidance as to the likely outcome of taking those options to a decision-maker. Because of its flexibility, modelling would be useful in addressing the nutrient requirements in terms of economics rather than simply achieving the biological production targets (Whittemore, 1993). The modelling approach would allow nutritionists and producers to be involved in 'catering' for the situations, thus having a significant impact on profitability of the pig enterprise.

Satisfying the Requirements and Nutrient Variability and Availability

Under commercial conditions, many factors such as biological variations in both the pig and nutrient sources, bioavailability and stability of nutrients in feed ingredients, interactions among the nutrients and non-nutritive factors, stress, physical and social environment, infectious diseases, parasite infestations and others can influence nutrition of the pig. Therefore, satisfying the nutrient needs of a population(s) of pigs, rather than individual animals, is a challenging task. Furthermore, it is conceivable that not only energy and amino acids, but also some vitamins and minerals, may play critical roles in pigs to express fully their genetic potential for growth, production or reproduction, as mentioned before. The ARC (1981) and NRC (1988) recommendations are generally designed to prevent nutrient deficiency signs and/or satisfy the requirements of average pigs. For the optimum performance of pigs, therefore, it is necessary to make appropriate adjustments to those recommendations according to various factors, including economical factors.

The formulation of pig diets that will satisfy the nutrient needs economically depends on the knowledge of: (i) the nutrient requirements; (ii) the nutrient contents of feed ingredients; and (iii) the availability of the nutrients in feed ingredients. The latter two are associated predominantly with the evaluation of feed ingredients, but they cannot be treated in isolation from that of the requirements. For instance, to evaluate protein quality, it is first necessary to establish the requirement for indispensable amino acids because the protein quality of any feed ingredient is simply a reflection of the limitations imposed by the amino acid composition and/or availability.

Nutrient variability

Considerable variation in the nutritional value of cereal grains, which form the basis of typical pig diets throughout the world, and other feed ingredients exists because of various factors (Wiseman and Cole, 1985). For instance, compared with the value of 85 g kg^{-1} reported by the NRC (1988), the CP content of more than one-half of corn samples contained less than 80 g kg^{-1} on an air dry basis (Reese, 1986). Similar variations in the CP content of cereal grains (and protein supplements) have been reported (Patience, 1996). Cereal grains are not only main sources of energy, but are also main sources of protein or amino acids, and generally supply 40–50% of the protein in the diet of growing pigs. Thus, their amino acid contents are very important (Lewis, 1991). It is reasonable to assume that the variability is associated with other nutrients in cereal grains, as well as many nutrients in other feed ingredients (Wiseman and Cole, 1985; NCR-42, 1993). In addition, the variability associated with various laboratories and analytical techniques (NCR-42, 1993; Patience, 1996; NCR-42 and S-145, 1997) may have to be considered.

Besides dealing with the variation in the content of nutrients in feed ingredients, nutritionists must face the issue of nutrient availability because not all of the energy, amino acids and others are available to the pig (Patience, 1996). For instance, amino acids may not be available because of an incomplete protein hydrolysis by proteolytic enzymes, suppression of enzymatic activity by inhibitors and/or inhibition of absorption. Similarly, mineral elements may be bound to phytate or fiber, or form complexes with others, and vitamins can exist as either precursor compounds or as coenzymes that may be bound or complexed in some manner, which render them unavailable to the pig.

The term bioavailability or availability can be defined as the degree to which an ingested nutrient in a particular source is absorbed in a form that can be utilized in the metabolic process by the animal (Ammerman *et al*., 1995); for amino acids, this involves the digestion, absorption, and utilization by the tissue after absorption. It is important to note that the availability influences not only dietary requirements but also tolerance of a nutrient as well. A number of comprehensive reviews have been written on the subject of nutrient availability including various articles on amino acids, minerals and vitamins that comprise the book edited by Ammerman *et al*. (1995).

Formulation of diets based on available nutrients

Simply because pigs can utilize only those nutrients available to them, it is reasonable to assume that expressing the requirements and formulating diets based on the available nutrients, rather than the total, would be more effective in precisely meeting the pig's needs. Most of the data on ME values have been derived mathematically from DE. Therefore, these two systems can be used interchangeably to a large extent, and the use of more easily determinable DE is preferred in pig diet formulation, as mentioned before. As for amino acids, in practice, most investigators have used apparent ileal digestibilities as an index of amino acid availability in feed ingredients. Although the values determined in such a manner are not perfect (Knabe, 1996), they are similar to values determined by other methods such as growth assays (NRC, 1988).

The NRC (1988) recommends the formulation of pig diets based on the available amino acids rather than the total when the availability of limiting amino acids in the ingredients is less than 70% or more than 90%. They also expressed the phosphorus requirements in terms of available phosphorus. Consideration of the availability of phytate phosphorus is important in pig nutrition because phosphorus is the third most expensive nutrient in the pig diet after energy and amino acids. Microbial phytase has been shown to be effective in improving the utilization of phytate phosphorus, as well as other mineral elements (Kornegay, 1996).

The competition between humans and animals for quality sources of nutrients is likely to increase continuously because of the ever-increasing world population, indicating the importance of exploring the potential of all sources as feed ingredients. Alternative feed ingredients have different feeding values because of variations in the nutrient contents and other factors such as palatability and handling property. Obtaining accurate information on the feed ingredients is, therefore, necessary to make appropriate adjustments for the formulation of diets that meet the nutrient standard in a cost-effective way. Apparent ileal digestibility of selected amino acids and availability of phosphorus in common feed ingredients are presented in Table 9.9.

Although other nutrients are equally important, consideration of the availability of energy, amino acids and phosphorus in diet formulation would contribute greatly to the efficiency and economics of pig production and a reduction of the release of unutilized nutrients into the environment. It is, however, questionable whether there is sufficient information on the nutritive value of individual feed ingredients (Close and Fowler, 1985). Therefore, there is very little agreement on how to address the availability issue in a day-to-day diet formulation, and there is also a question regarding whether this practice will improve the precision of diet formulation sufficiently to meet the needs of the industry (Patience, 1996). Further progress must be made in developing procedures to describe the true nutritional value of feed ingredients so that practical, convenient, cost-effective and environmentally friendly pig diets can be formulated.

FACTORS AFFECTING NUTRIENT REQUIREMENTS AND/OR EFFICIENCY OF NUTRIENT UTILIZATION

Voluntary Feed Intake

In North America, growing pigs and lactating sows generally are allowed to consume feed *ad libitum*, whereas feed intakes of developing gilts, boars and pregnant females are restricted to accommodate their nutritional needs. Voluntary feed intake is expressed in terms of DE because this is the energy introduced into the biological system, and the DE intake (DE_i; kJ day^{-1}) can be predicted by the following equations (NRC, 1986):

Suckling pig $DE_i = 46.9\ D - 634.7$ (9.4)

Weanling pig $DE_i = 1933\ BW - 40.7\ BW^2 - 6397$ (9.5)

Growing pig $DE_i = 55071\ (1 - e^{-0.0176\ BW})$ (9.6)

Lactating sow $DE_i = (56067 + 2494\ D) - 72.0\ D^2$ (9.7)

where D is age of the pig and the day of lactation for the suckling pig and lactating sows, respectively, and BW is in kg for the weanling and growing pig.

Feed intake of the pig is determined largely by the energy density of the diets, and it is generally assumed that pigs can adjust a voluntary feed intake

Table 9.9. Apparent ileal digestibilities of selected amino acids and estimates of biological availability of phosphorus in pig feed ingredients[a].

	Amino acids (%)[b]				Phosphorus (%)[c]	
Feed ingredient	Lysine	Tryptophan	Threonine	Methionine	Average	Range
Alfalfa meal	—	—	—	—	100	—
Barley, grain	73	73	70	82	31	—
Beans, broad (*Vicia faba*)	82	68	75	73	—	—
Blood meal	81	—	82	—	—	—
Bone meal	—	—	—	—	82	—
Canola meal	75	—	67	84	—	—
Corn, grain	80	70	73	89	15	9–29
Corn, high moisture	—	—	—	—	49	42–58
Cottonseed meal	65	73	63	70	21	0–42
Defluorinated rock phosphate	—	—	—	—	87	83–90
Dicalcium phosphate	—	—	—	—	100	—
Fish meal	80	—	76	84	100	—
Meat and bone meal	64	53	56	73	93	—
Oat groats	82	81	78	89	—	—
Oats	58	59	53	75	30	23–36
Peanut meal	79	—	—	—	12	—
Rice bran	—	—	—	—	25	—
Rye, grain	68	62	62	80	—	—
Sorghum, grain	80	75	73	85	22	19–25
Sorghum, high moisture	—	—	—	—	43	42–43
Soybean meal	87	81	77	86	38	36–39
Soybean meal, dehulled	85	78	74	88	25	18–35
Triticale	82	—	74	85	—	—
Sunflower meal	72	—	71	84	—	—
Wheat, grain	80	78	74	85	50	40–56
Wheat bran	—	—	—	—	35	—
Wheat middlings	—	—	—	—	45	34–55

[a]Based on NRC (1988).
[b]Values represent the percentage of the total amino acid contained in the feed ingredient that has disappeared from the digestive tract of growing swine when digesta arrive at the terminal ileum.
[c]Relative to the availability of phosphorus in monosodium phosphate (100%).

to achieve a constant energy intake (NRC, 1986). Such control mechanisms, however, may not work under extreme conditions because of a physical limitation and a lack of gut fill with diets of low and high nutrient densities, respectively. Besides the dietary energy density and ambient temperatures, the adequacy of dietary protein or amino acids (Henry, 1985) and amino acid disproportions (Pond *et al.*, 1969) have also been shown to influence feed intake, indicating the importance of amino acids in this regard.

By definition, appetite of the animal is a function of the nutrient requirement (Whittemore, 1993). Voluntary feed intake dictates the amounts of indispensable nutrients consumed by the animal; consequently, it is a major factor determining the growth, health, production and/or reproduction of the pig. Manipulating a feed intake and/or understanding various factors that are known to influence the feed intake and making appropriate adjustments would, therefore, contribute greatly to successful pig production.

Amino Acid and Energy Interrelationships in Growing Pigs

The subject of energy and amino acid relationships has been reviewed thoroughly by the SCA (1987), Chiba (1989) and Edwards and Campbell (1993). Nutritionally, energy and amino acids are very closely related, and it is almost impossible to discuss one without considering the other. Considering the effect of dietary energy on the intake of pigs given *ad libitum* access to feed, it seems logical that the amino acid levels in the diet should be related to its energy density. However, investigations on the need to adjust amino acids or protein according to changes in the energy density yielded conflicting results (Allee and Hines, 1972; Tribble *et al.*, 1979; Chiba *et al.*, 1985, 1987). Factors that may have been responsible for the inconsistent responses have been summarized by Chiba (1989). Chiba *et al.* (1991a,b) conducted research to verify the need to adjust dietary amino acids according to the dietary energy content by using three amino acid levels that were either adjusted for five DE levels or unadjusted for three DE levels. Their results demonstrate the need to adjust dietary amino acid levels in concert with changes in energy densities so that pigs can consume adequate amounts of amino acids.

Simply because an energy intake can influence the rate of protein accretion in the pig, expressing the amino acid requirements in terms of dietary energy density would be beneficial. The concept of using a constant amino acid to energy value is, however, only valid if the relationship between energy intake and rate of protein accretion is linear (SCA, 1987). This approach has been adopted by ARC (1981), and their recommendations imply that this concept holds under conditions of protein adequacy. The relationship seems to be linear for young pigs (Campbell *et al.*, 1983), but not for pigs weighing 45–90 kg (Campbell *et al.*, 1985). As indicated by the SCA (1987), the growing pig's potential for protein growth from birth to 50 kg seems to lie beyond the upper limit of appetite, whereas it lies within the limits of appetite for pigs weighing 50–100 kg. This implies that diets of high energy density can be offered *ad libitum* to pigs weighing up to 50 kg without excessive fat accretion or reducing feed efficiency, but *ad libitum* feeding of such diets to pigs weighing 50–100 kg would cause undesirable results. Although it depends on sex and genotypes, the amino acid to energy value would decline continuously once pigs reach the phase where an energy intake exceeds maximum protein accretion.

The relationship of energy and amino acids in a pig's diet seems to be less critical because pigs can grow well with various energy and amino acid levels. However, in terms of protein or lean accretion, which is the primary objective of today's pig production, it is not an appropriate generalization. Conceivably, there is a combination of energy, amino acids and other conditions that can lead to maximum utilization of nutrients to produce desirable animal products.

Effects of Environmental Factors

Temperature is perhaps the most important component of the environment. Assuming the feed intake at 15°C as 100 and the temperature increased from 5 to 30°C, a reduction in the feed intake can be predicted by the following equation (NRC, 1986):

$$\%\ \text{change} = 126.3 - 1.65\ T \qquad (9.8)$$

where percent change reflects the deviation from a feed intake at 15°C, and T is the reported ambient temperature in degrees Celsius. The effect of BW on the optimum temperature (T_o) can be described by the following equation (NRC, 1986):

$$T_o = 26 - 0.0614\ \text{BW} \qquad (9.9)$$

where T_o is in degrees Celsius and BW in kg. The temperature can be modified by several factors, and the term effective ambient temperature (EAT) has been used to describe the temperature that the animal actually experiences; the EAT can be affected by many factors (NRC, 1986). With an assumption that the deviation from T_o influences the feed intake, the correction in DE_i between 5 and 30°C can be described by the following equation (NRC, 1986):

$$\%\ \text{change in } DE_i = (T_o - \text{EAT})0.0165. \qquad (9.10)$$

Temperatures below the critical temperature will stimulate a feed intake, but the additional feed consumed would be used for the increased energy demands, thus reducing the efficiency of feed utilization (Holmes and Close, 1985). On the other hand, warm or hot temperatures decrease voluntary feed intake and would be likely to reduce the rate and efficiency of growth. To compensate for a reduced feed intake at high temperatures, it would be necessary, therefore, to increase the concentrations of certain components of the diet, such as amino acids and energy. In addition, it is well known that floor space allowance and group size can influence a feed intake and growth rate, but their impact on the nutrient content of the diet is not clear at this time (e.g. Brumm and Miller, 1996). Although the description or consideration of the animal's environment has focused mainly on the aspect of physical environment, other dimensions such as the social and infectious environment may have to be considered when determining the pig's nutritional needs in the future (Kyriazakis, 1996).

Effect of Sex and Genotypes

It is well known that boars have a greater potential for lean accretion than gilts (Campbell *et al.*, 1983, 1985) and castrates (Campbell and King, 1982), while gilts have a higher protein accretion rate than castrates (Just, 1984). Similarly, carcass quality of boars is generally considered superior to that of gilts and barrows (Taverner *et al.*, 1977), thus it is likely that their nutrient requirements would be different (Campbell and King, 1982; Campbell *et al.*, 1983, 1985). Because of these differences, it might be advantageous to consider split-sex feeding and/or management of pigs (Fuller, 1985) to optimize profitability of the pig enterprise. However, neither the ARC (1981) nor the NRC (1988) differentiates possible variations in their recommendations, possibly due to an inconsistent sex effect on the pig performance, especially with *ad libitum* feeding (Taverner *et al.*, 1977), indicating that further research is required in this area.

Similarly, differences in growth rate and body composition have been recognized among different strains and breeds of pigs. Pigs selected for or against subcutaneous fat or growth rate show physiological and metabolic alterations (e.g. Steele *et al.*, 1974; Steele and Frobish, 1976; Pond *et al.*, 1980). It is, therefore, reasonable to assume that pigs with distinct genotypes may differ in their responses to the level of nutrients, efficiency of nutrient utilization, interrelationships among the nutrients, etc. In some herds, optimum production may be achieved by feeding diets containing marginal levels of nutrients, thus reducing feed costs. Conversely, in some instances, pigs may respond to higher levels of nutrients than those normally recommended, thus improving the productivity and possibly the efficiency. Therefore, nutritional management and/or recommendations may have to reflect the genetic potential of pigs for growth and protein accretion in order to achieve overall productivity and efficiency of pigs, which can lead to greater profitability of the pig enterprise.

Effects of Nutritional History

Most of the feed for the whole pig enterprise is consumed by finisher pigs. Therefore, any improvement in the efficiency of amino acid and energy utilization during the finisher phase contributes greatly to the overall efficiency of pig production. It has been demonstrated over the years that the growth performance of weanling and grower pigs can be improved by offering diets containing various special ingredients and high levels of energy and amino acids, respectively. Compensatory growth responses after a period of feed (e.g. Prince *et al.*, 1983) or protein restrictions (e.g. Chiba, 1994, 1995) in young pigs have been reported. Possible reasons for the compensatory response (e.g. Chiba, 1994) and the importance of the nutritional status of pigs in the subsequent phase on the ability of pigs to exhibit compensatory growth (Campbell and Dunkin, 1983; Kyriazakis *et al.*, 1991) have been suggested.

These findings indicate that the early nutritional history may have little importance in terms of overall rate and efficiency of growth. The available evidence is, however, far from conclusive, as exemplified by recent reports (Henry, 1995; Chiba *et al.*, 1997). It is likely that the extent of compensatory response is dependent on the age of pigs and the degree and duration of dietary energy and/or amino acid restrictions. Further research needs to be conducted to evaluate fully the potential implications of nutritional history on the optimum production of pigs.

PIG WASTES AND THE ENVIRONMENT

Pollution of the environment with N and phosphorus is a major problem in many parts of the world (Lenis, 1989), and the management of wastes and odours has become a major issue facing the pig industry. Large amounts of N excreted in animal wastes can lead to the leaching of nitrate from the wastes to the surface, ground and drinking water, and to odorous emissions because many odorous compounds originate from undigested dietary protein and other nitrogenous compounds. Likewise, excess phosphorus can lead to undesirable eutrophication of surface water.

Nutritional means to manipulate microorganisms in the intestinal tract by using various feed additives, particular carbohydrates or decreasing dietary CP, may be effective in reducing the odour emissions from pig wastes (Cromwell, 1996). There are several potential ways to reduce N excretion in the pig: (i) avoid too generous safety margins in dietary protein; (ii) reduce excesses of unneeded individual amino acids; (iii) supplement limiting amino acid(s) to satisfy the needs (Henry *et al.*, 1992; Page *et al.*, 1993b); and (iv) phase and split-sex feeding (Fuller, 1985; Lenis, 1989); together with other management practices that improve the overall efficiency of feed utilization.

Phosphorus excretion can be reduced by using similar approaches, e.g. avoiding generous safety margins, phase- and split-sex feeding, and by enhancing the utilization of phytate phosphorus. Phytate phosphorus can be utilized only after a hydrolysis by phytase, and microbial phytase has been shown to be very effective in improving phosphorus availability of plant feed ingredients in pigs and poultry (Kornegay, 1996). Because phytates are known to limit the availability of multivalent cations and possibly protein, the use of phytase is beneficial not only in enhancing phosphorus utilization and reducing its excretion, but also in improving the availability of other mineral elements and amino acids. However, a practical application of microbial phytase in pig nutrition depends on many factors, including the need to reduce the excretion of phosphorus and other mineral elements and the availability and cost of phytase.

Because of its impact on the air, land and water, the pig industry seems to be especially vulnerable to environmental criticism. Public concerns about environmental issues are, in part, a result of the concentration of the animal agriculture on a relatively small land area (i.e. fewer, but larger, intensified operations), and will continue to increase in the future. Environmental issues cannot be ignored, and exploring all possible avenues and implementing effective methods to alleviate public concerns are, therefore, essential for a sustainable pig industry.

CONCLUSIONS

The main goal of diet formulation and feeding strategy in commercial pig production is to maximize profits, which does not necessarily imply maximal animal performance. In recent years, management of wastes and odours associated with intensive animal production has become a major issue facing animal agriculture. The pig industry is especially vulnerable to the environmental criticism because of its impact on the air, land and water. Therefore, exploring all possible avenues and implementing effective methods to reduce potential pollutants, as well as maximizing the economic efficiency, can have a significant impact on ensuring successful pig production in the future.

Offering diets containing just enough nutrients to meet, but not exceed, the needs of the pig would be beneficial in: (i) maximizing the economic efficiency; (ii) optimizing the utilization of quality sources of nutrients, for which pigs compete with humans; and (iii) alleviating public environmental concerns by reducing the excretion of unutilized nutrients. Such optimum feeding strategies involve consideration of a multitude of factors such as genetic potential, nutritional history and voluntary feed intake of the pig, variability, bioavailability and stability of nutrients in feed ingredients, various types of stress, the physical and social environment and possible interactions among those factors. Considering the effects of those factors, estimating the nutrient requirements with accuracy and precision, or satisfying the needs of a population(s) of pigs, rather than individual animals, is a challenging task. This contention implies that no single set of estimates is likely to satisfy the requirements of all animals.

Nutritional management and/or recommendations should take into account various factors known to influence nutrition of the pig, and appropriate adjustments must be made to achieve overall productivity and efficiency of pig production. A modelling approach, therefore, might be the only defensible means of incorporating all the information necessary to establish the nutrient requirements and/or to formulate efficient, practical, economical and environmentally friendly diets. Such an approach would provide the direction and magnitude of the response and sensitivity of the production system to a tactical or strategic change so that more effective financial and management decisions can be made. Because of its flexibility, modelling would be useful in defining nutrient requirements and satisfying the needs of pigs in terms of the profitability and environmental accountability; this is essential for a sustainable pig industry, as opposed to simply achieving biological production targets.

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