NUTRIENT REQUIREMENTS OF SWINE

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Committee on Nutrient Requirements of Swine

Board on Agriculture and Natural Resources

Division on Earth and Life Studies

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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by **Dale E. Bauman,** Cornell University. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the author committee and the institution.

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Preface

This eleventh revised edition of the *Nutrient Requirements of Swine* builds on the previous editions published by the National Research Council. The tenth edition,[1] in particular, provided a major foundation for the current edition. Although a great deal of new research has been published during the last 15 years and there is a large amount of new information, for many nutrients (e.g., vitamins) there is little or no new research data on requirements.

The committee established the principle that without new research results indicating a need to revise a nutrient requirement, the values published in the tenth edition would be retained. This principle was also applied to the text. Therefore, portions of the text from the tenth revision were also retained. In this sense the report is truly a "revised edition," and will eliminate the need for a reader to refer to previous editions.

In contrast, the committee decided that the tables of feed ingredient composition were due for a major update. Thus, as explained in Chapter 17, the committee conducted an exhaustive review of published data and completely revised both the format and content of the ingredient composition tables.

[1]NRC (National Research Council). 1998. Nutrient Requirements of Swine, Tenth Edition. Washington, DC: National Academy Press.

Summary

Since 1944, the National Research Council has published 10 editions of the *Nutrient Requirements of Swine*. The publication has guided nutritionists and other professionals in academia and the swine and feed industries in developing and implementing nutritional and feeding programs for swine. The swine industry has undergone considerable changes since the tenth edition was published in 1998[1] and some of the requirements and recommendations set forth at that time are no longer relevant or appropriate. This eleventh edition has been revised to reflect these changes.

The task given to the committee is presented in Appendix B. In brief, the committee was asked to prepare a report that evaluates the scientific literature on the energy and nutrient requirements of swine in all stages of life. Other elements of the task included: information about feed ingredients from the biofuels industry and other new ingredients, requirements for digestible phosphorus (P) and concentrations of digestible P in feed ingredients, a review of the effects of feed additives and the effects of feed processing, and strategies to increase nutrient retention and thus reduce fecal and urinary excretions that could contribute to environmental pollution.

The study was supported by grants from the Illinois Corn Marketing Board, the Institute for Feed Education & Research, the National Pork Board, the Nebraska Corn Board, the Minnesota Corn Growers Association, the U.S. Food and Drug Administration, and by internal NRC funds derived from sales of publications in the Animal Nutrition Series.

To accomplish the task, the text has been expanded considerably to enlarge on existing topics and to add new topics. Nutrient requirement tables have been revised and revamped to reflect new research findings. The computer models that generate estimates of energy and nutrient requirements have undergone major updates and the tables of feed composition have been revised completely with a comprehensive review of new information. The report begins with chapters on energy and the six classes of nutrients. This is followed by a chapter on the use of computer models to determine nutrient requirements of swine. The remaining chapters cover factors that influence nutrient utilization and responses to nutrients and also the tables of requirements and nutrient composition.

The first chapter deals with energy. After describing the classical scheme of partitioning energy from gross to net energy and its use in swine nutrition, the application of computer modeling to defining energy requirements is discussed. The section on net energy has been revised substantially to calculate net energy from digestible and metabolizable energy and from the chemical composition of feedstuffs. The new chapter contains discussions of the effects of immunocastration and ractopamine on energy utilization.

Chapter 2, on proteins and amino acids, begins with a discussion of the distinction between dietary essential and dietary nonessential amino acids and also the amino acids whose dietary essentiality is conditional on other dietary components and the physiological state of the animal. Sources of amino acids, both intact proteins and crystalline amino acids, are then reviewed. The chapter examines the various means of determining and expressing amino acid requirements (including empirical approaches, the ideal protein concept, and factorial calculations) and reviews experiments to determine amino acid requirements of growing pigs, sows, and boars.

Lipids, which were discussed within the energy chapter of the previous edition, are now given a chapter of their own (Chapter 3). The chapter begins with a discussion of lipids as a source of energy and the effects of dietary fat on swine performance throughout the life cycle and then reviews the specific effects of essential and bioactive fatty acids. The effects of fat intake on pork fatty acid composition are then discussed and the calculations of iodine value and iodine value product are described. The final section of the chapter reviews quality measures of fat such as oxidation status and lipid analysis.

[1]NRC (National Research Council). 1998. Nutrient Requirements of Swine, Tenth Edition. Washington, DC: National Academy Press.

Carbohydrates were also covered in the energy chapter in the previous edition but are now reviewed in Chapter 4. Although swine do not have specific requirements for dietary carbohydrates or fiber, most of the energy in pig diets originates from carbohydrates of plant origin. The chapter describes the major categories of carbohydrates, their digestion, and the absorption of energy-yielding nutrients.

Water, sometimes described as the forgotten nutrient, is reviewed in Chapter 5. The majority of the chapter is devoted to the water requirements of all classes of swine, but there are also sections on the functions of water, turnover of water, and water quality.

The mineral nutrition of swine remains an active area of research. Chapter 6 provides an update on new findings for both macro- and microminerals. Other issues, such as bioavailability and the use of certain minerals as pharmacological agents, are also reviewed.

An update of the 1998 review of vitamin requirements is provided in Chapter 7. The chapter is divided into fat-soluble and water-soluble vitamins. The relative bioavailability and stability of vitamins used in feeds are also covered. There is also discussion of toxicity and maximum tolerable levels for vitamins where data are available.

The use of computer models to estimate energy and amino acid requirements was introduced in the previous edition of this publication. The three models developed then (growing-finishing pigs, gestating sows, and lactating sows) have been updated and expanded. As described in Chapter 8, the three models are now mechanistic, dynamic, and deterministic in representing the biology of nutrient and energy utilization at the whole-animal level. In addition to energy and amino acid requirements, the new models estimate requirements for calcium (Ca) and P. Other new features are the inclusion in the growing pig model of the effects of including ractopamine and immunization of entire males against boar taint. The fundamental concepts represented in the models and the specific equations used in the calculations are described in this chapter.

The expansion of the biofuels industry, especially the production of ethanol from corn, has resulted in large amounts of coproducts (sometimes called byproducts) that are now used in animal feeding. Chapter 9 reviews information on the feeding value of these products for swine. Although the emphasis is on coproducts from corn and soybean meal, other plant and animal coproducts are also covered.

Chapter 10 addresses nonnutritive feed additives, such as antimicrobial agents and exogenous enzymes. This chapter is an update of material in the previous edition with new information on several different categories of substances.

An issue of increasing concern, making headlines in 2007 because of the adulteration of pet food with melamine, is both the accidental and deliberate contamination of animal feeds. Chapter 11 reviews feed contaminants and divides them into three primary groups: chemical, biological, and physical. In the United States, the safety and adequacy of animal feed is regulated by the Food and Drug Administration (FDA) and some of the key FDA documents are cited in the chapter.

Nutrient utilization may be influenced by how ingredients are processed and how diets are prepared. This topic is addressed in Chapter 12. The effects of mechanical processing, such as extrusion, grinding, and pelleting, on nutrient digestibility and pig performance are reviewed. Although most forms of processing, especially of ingredients with high contents of complex carbohydrates, increase pig performance, the benefits have to be weighed against the costs of the processing.

Chapter 13 reviews the digestibility of nutrients and energy by swine. Topics covered are protein and amino acids, lipids, carbohydrates, P, and energy. The chapter describes the reasons for measuring digestibility and the primary methods used. Values for the digestibility of ingredients fed to swine are included in the tables of nutrient composition.

The topic of feeding practices that minimize nutrient excretion was introduced in the previous edition of the report, and it has been expanded in Chapter 14 to include additional information on the influence of nutrition on nutrient excretion and the environment. Nutrients discussed are nitrogen, Ca and P, trace minerals, sulfur, and carbon. The effects of diet formulation on gaseous emissions, especially so-called greenhouse gases and ammonia, are also reviewed.

In Chapter 15, research priorities are identified, including specific areas and topics where research is needed to add new information or to confirm or refute data that are limiting. Many areas of research needs are documented, but the most important needs relate to amino acid, Ca, and P requirements of all categories of pigs, with the greatest emphasis on the sow.

Chapter 16 contains a series of tables of the nutrient requirements of all classes of swine. Requirements are expressed on an "as-fed" basis. The committee critically evaluated published studies to arrive at the estimates presented. As such, values in these tables are the best estimates of the committee rather than an average of literature values. As in previous editions, the estimated nutrient requirements in this publication are minimum standards without any safety allowances. Therefore, they are not intended to be considered as recommended allowances. Professional nutritionists may choose to increase the levels of some of the more critical nutrients to include "margins of safety" in some circumstances (this comment does not apply to selenium because it is regulated by the FDA in the United States). Another important point is that, for minerals and vitamins, the estimated requirements include the amounts of these nutrients that are present in the natural feedstuffs and are not estimates of amounts of nutrients to be added to diets.

Chapter 17 consists of tables of feed ingredients for 122 feedstuffs commonly fed to swine, including average composition values. These tables have been completely revised since the previous edition and are presented on individual pages for each ingredient. The literature was reviewed with emphasis during the last 15 years to arrive at ingredient composition. If no new data were available, then the search was extended to older literature. In some instances, no data were found; in those instances, combinations of data from other published tables were used as sources of information.

All livestock industries need to focus on efficient, profitable, and environmentally conscious production, and the swine industry is no exception. The nutrition of swine plays a major role in each of these areas of production, and diet cost represents the major cost of swine production. Inefficient nutrition utilization reduces profitability and efficiency and can harm the environment. This report represents a comprehensive review of the most recent information available on swine nutrition and ingredient composition that will allow optimum swine production. New ingredients resulting from ethanol production are described, as well as feed contaminants and environmental concerns. Use of this report will be an invaluable guide to support efficient and environmentally aware swine production.

1

Energy

INTRODUCTION

The original definition of energy relates to the potential capacity to carry out work. The context in which animal nutritionists evaluate energy is typically the oxidation of organic compounds. Although there are many forms of energy, nutritional applications focus primarily on chemical and heat energy. The description of energy systems for swine is complicated by the hierarchy of energy use in the animal and the complexity of diets and ingredients commonly used. Models have been developed that accurately and mechanistically describe elements of energy metabolism in the pig; however, this chapter will be limited to components of energy nutrition that elucidate the description of feed-ingredient energy values and energy requirements described in this publication. The energy system used to express requirements for pigs has developed from using total digestible nutrients (NRC, 1971) to metabolizable energy (ME) and net energy (NE). The focus of this chapter will be on research and energy concepts disseminated since the last revision of swine energy and nutrient requirements (NRC, 1998). Critical research published before the last revision will also be discussed. Additionally, concepts of swine energy metabolism related to the development and documentation of energy utilization in the computer simulation model (Chapter 8) will be reviewed.

DEFINITION OF TERMS

Energy content of feedstuffs, waste products, and elements of heat loss can be expressed as calories (cal), kilocalories (kcal), or megacalories (Mcal). In addition, energy content is often expressed in Joules (J) and the conversion 4.184 J = 1 cal is used. The following discussion of energy partitioning and utilization in the pig is largely empirical and encumbered with a large number of abbreviations. The reader can review NRC (1981) for a review of terms used to describe feed energy content and energy requirements. Energy components defined hereafter will be expressed in kilocalories.

PARTITIONING OF ENERGY

Figure 1-1 illustrates the classical partitioning of feed gross energy (GE). Energy requirement systems used for swine have been developed from the construct depicted in Figure 1-1. The partitioning of energy depicted in Figure 1-1 divides energy intake into three general categories: heat, product (tissue) formed, and waste products. It is important to remember that energy values assigned to ingredients and energy requirements (albeit determined quite differently) are affected by the chemical-physical makeup of the ingredient

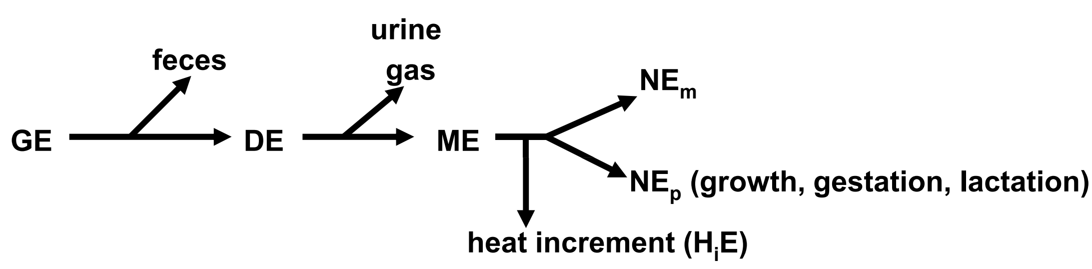

FIGURE 1-1 Partitioning of nutrient/dietary energy.

and the physiological state of the pig (growth, gestation, lactation). The following sections will review the components of Figure 1-1 as affected by feed chemical composition, physiological state, and environment. Although energy requirements in this publication are modeled and expressed in terms of ME (effective ME; see Modeling Energy Utilization—The Concept of Effective Metabolizable Energy section), in the feed database energy contents of feed ingredients are listed in each of the three common systems (i.e., GE, digestible energy [DE], metabolizable energy [ME], and net energy [NE]). Therefore, diets can be evaluated using various energy bases (e.g., DE, ME, or NE). The predictions of feed energy values presented hereafter are empirically based and must be used judiciously. These regression equations were developed under specific conditions (inputs) and the reader is encouraged to consult the primary publication from which the equation(s) were developed.

Gross Energy

Gross energy is the amount of energy produced when a compound is completely oxidized. All organic compounds contain a quantity of GE. Determination of the GE content of feces, urine, gas, and various products is used to help elucidate the calculations of DE, ME, and NE (see subsequent sections). The GE or heat of combustion is determined directly using calorimetry. Alternatively, the following values can be used to estimate the GE content (kcal/kg) of specific nutrient classes: carbohydrates, 3.7 (glucose and simple sugars) to 4.2 (starch and cellulose); protein, 5.6; and fat, 9.4 (Atwater and Bryant, 1900). Also, if the chemical composition of a feed ingredient or diet is known, GE (kcal/kg) can be predicted by the following equation:

$$\begin{aligned} GE = 4{,}143 &+ (56 \times \%\ EE) \\ &+ (15 \times \%\ CP) \\ &- (44 \times \%\ Ash) \end{aligned}$$

(Ewan, 1989) (Eq. 1-1)

where EE is ether extract and CP is crude protein.

Because within each respective class of carbohydrates, fats, and proteins the GE content is similar, the determination of GE is of little value in discriminating among or ranking feed ingredients and diets.

Digestible Energy

Digestible energy is the result of subtracting the GE in feces from dietary GE (Figure 1-1). Typically, the GE in feces is not partitioned between energy of endogenous vs. feed origin; therefore, most published DE values are apparent DE values. The estimation of DE densities can be determined directly in animal studies (Adeola, 2001) or by using equations that predict DE from chemical composition. Several approaches have been proposed to predict DE (kcal/kg of DM) from dietary chemical composition:

$$\begin{aligned} DE = 1{,}161 &+ (0.749 \times GE) \\ &- (4.3 \times Ash) \\ &- (4.1 \times NDF) \end{aligned}$$

(Noblet and Perez, 1993) (Eq. 1-2)

$$\begin{aligned} DE = 4{,}168 &- (9.1 \times Ash) \\ &+ (1.9 \times CP) \\ &+ (3.9 \times EE) \\ &- (3.6 \times NDF) \end{aligned}$$

(Noblet and Perez, 1993) (Eq. 1-3)

where NDF is neutral detergent fiber (all chemical components are expressed as g/kg DM). It is important that predicted DE (as well as ME and NE prediction equations) values are carefully evaluated. In particular, it is crucial that the user reviews the range of inputs (independent variables) when making extrapolations. Also, equations were often developed using complete diets, and caution is needed when extrapolating to individual ingredients.

In addition to chemical composition, a number of other factors affect digestibility and thus DE content. Noblet and Shi (1993) and Le Goff and Noblet (2001) demonstrated that energy digestibility increases as pigs mature (growing pigs vs. sows), with the increase in energy digestibility being associated with greater digestion of dietary fat and fiber (Noblet and Bach Knudsen, 1997). Because of the difference in apparent digestibility of energy between growing pigs and sows, separate values for DE, ME, and NE have been proposed (Noblet and van Milgen, 2004). This approach, albeit more precise, was not used in designation of the feed values included within the feed ingredient database in this publication (i.e., only one DE, ME, and NE value is associated with each feed ingredient) and were derived using growing-finishing pigs.

Feed intake has little impact on energy digestibility (Haydon et al., 1984; Moter and Stein, 2004). Several studies have indicated that social interaction (group-fed vs. individually fed pigs) affects feed intake. In group-housed pigs, increased pig density decreased energy digestibility because of a greater passage rate (Bakker and Jongbloed, 1994). Additional factors associated with feed processing and heat processing affect digestibility and are reviewed in Chapter 12 (Feed Processing).

Although these aforementioned factors affect digestibility and DE values for swine, the nutrient database and listed energy requirements do not make any corrections for those factors.

Metabolizable Energy

Digestible energy minus the GE in urine and fermentation gases equals ME (Figure 1-1). Metabolizable energy represents a significant proportion of DE (92-98%; NRC, 1981, 1998). Gas losses can vary and are typically low for conventional diets fed to growing-finishing pigs (0.5% DE; Noblet et al., 1994), but can be as high as 3% of DE in sows fed high-fiber diets (Ramonet et al., 1999). Methane production by pigs can be estimated directly from fermentable fiber content (Rijnen, 2003). The major factor defining the proportion of DE converted to ME is the GE in urine. Urinary energy losses primarily arise from excreted nitrogen (primarily urea); therefore ME/DE can be estimated from the digestible CP content (it is assumed that a constant proportion of digestible protein intake contributes to urinary N excretions):

$$ME/DE = 100.3 - (0.021 \times CP)$$
(Le Goff and Noblet, 2001) (Eq. 1-4)

where CP is expressed as g/kg DM.

The amount of digestible protein intake converted to urinary N is variable and dependent on amino acid balance (protein quality) and protein retention in the pig.

The ME (kcal/kg) can be predicted directly from nutrient composition:

$$ME = 4{,}194 - (9.2 \times Ash) + (1.0 \times CP) + (4.1 \times EE) - (3.5 \times NDF)$$
(Noblet and Perez, 1993) (Eq. 1-5)

$$ME = (1.00 \times DE) - (0.68 \times CP)$$
(Noblet and Perez, 1993) (Eq. 1-6)

where chemical components are expressed as g/kg DM and DE is expressed as kcal/kg.

Net Energy

Metabolizable energy minus heat increment energy (H_iE) (see the section Components of Heat Production) equals NE (NE for maintenance [NE_m] and NE for production [NE_p]). It is generally assumed that NE is the ideal basis to express energy needs of pigs (Noblet and van Milgen, 2004). Net energy values and systems have been based on comparative slaughter (Just, 1982) or indirect calorimetry (Noblet et al., 1994) experiments using growing-finishing pigs. Adoption of the NE approach derived from indirect calorimetry studies led to the development of NE prediction equations based on digestible nutrient composition (Noblet et al., 1994) and has also been applied to low-protein amino acid supplemented diets (Le Bellego et al., 2001). Recently, the comparative slaughter approach has been used in North America to predict NE values for soybean oil and choice white grease (Kil et al., 2011).

A number of concerns have been raised about the application of NE prediction equations for diets or feed ingredients. It is important to remember that NE prediction equations were developed from complete diets and caution is essential when applying predictions to individual ingredients (this is applicable to DE and ME values as well). However, few experiments have been implemented to determine NE values for individual ingredients. Errors in estimating NE_m (often derived from measures of fasting heat production [FHP]) can be substantial largely because of challenges quantifying FHP, and impact directly estimated NE values (Birkett and de Lange, 2001a). Four equations are identified to predict NE (kcal/kg DM):

Adapted from Noblet et al. (1994; following three equations); all nutrient and digestible nutrient contents are expressed as g/kg DM

$$NE = (0.726 \times ME) + (1.33 \times EE) + (0.39 \times Starch) - (0.62 \times CP) - (0.83 \times ADF)$$
(Eq. 1-7)

$$NE = (0.700 \times DE) + (1.61 \times EE) + (0.48 \times Starch) - (0.91 \times CP) - (0.87 \times ADF)$$
(Eq. 1-8)

where ADF is acid detergent fiber, and ME and DE are expressed as kcal/kg.

$$NE = (2.73 \times DCP) + (8.37 \times DEE) + (3.44 \times Starch) + (2.89 \times DRES)$$
(Eq. 1-9)

where DCP = digestible CP, DEE = digestible EE, and DRES = DOM – (DCP + DEE + Starch + DADF); DRES = digestible residue, DOM = digestible organic matter, DCP = digestible CP, DEE = digestible EE, and DADF = digestible ADF.

A fourth equation was adapted from Blok (2006)

$$NE = [(2.80 \times DCP) + (8.54 \times DEE_h) + (3.38 \times Starch_{am}) + (3.05 \times Sug_e) + (2.33 \times FCH)]$$
(Eq. 1-10)

where DEE_h = digestible crude fat after acid hydrolysis; $Starch_{am}$ = enzymatically digestible fraction of starch according to the amyloglucosidase method; Sug_e = enzymatically degraded fraction of the total sugar; FCH (fermentable carbohydrate) = $Starch_{am(ferm)}$ [$Starch_{am}$ that is fermentable, assume 0 except for potato starch] + Sug_{ferm} (fermentable sugar) + DNSP (digestible nonstarch polysaccharide); and DNSP = DOM – DCP – DEE_h – $Starch_{am}$ – (CorrFactor ×

Sug_{total}); $Sug_{total} = Sug_e + Sug_{ferm}$; assume CorrFactor = 0.95; all nutrient and digestible nutrient contents are expressed as g/kg DM.

Regardless of the comparison of NE estimates, it is clear that alternative databases are needed to predict NE using the Blok (2006) equation, which are not included in the publication. Most importantly, prediction of NE was reconciled with the current feed ingredient database. A large effort was undertaken to solicit values from the literature, and relatively few starch, sugar, and estimates of CP and EE digestibility were acquired. The comprehensive values needed to predict NE were not available in the literature base reviewed in development of the feed ingredient database in the current report. Although alternative feed ingredient databases exist (Sauvant et al., 2004; CVB, 2008), development of the NRC feed ingredient database relied almost exclusively on composition values derived from the published literature.

Based on the review to date and the difficulty acquiring nutrient analyses for sugar and digestibility values, the equation using nutrient composition (Eq. 1-8; Noblet et al., 1994) was used to predict NE values in Table 17-1.

COMPONENTS OF HEAT PRODUCTION

Total heat production (HE) is allocated to maintenance (H_eE), heat increment (H_iE), activity (H_jE), and maintaining body temperature (H_cE; see NRC [1981] for terminology):

$$HE = H_eE + H_iE + H_jE + H_cE \quad \text{(Eq. 1-11)}$$

The conversion from ME to NE (maintenance and growth, pregnancy, and lactation) is affected by H_iE:

$$ME = H_eE + H_iE + NE_p \text{ (growth, milk, conceptus)} \quad \text{(Eq. 1-12)}$$

Therefore, in addition to allocating ME included in a defined product (protein, lipid), H_eE (generally considered FHP) and H_iE are critical to the overall efficiency of ME use for maintenance and production. Heat increment can be partitioned according to

$$H_iE = H_dE + H_rE + H_fE + H_wE \quad \text{(Eq. 1-13)}$$

where H_dE = heat of digestion and assimilation, H_rE = heat of tissue formation, H_fE = heat of fermentation, and H_wE = heat of waste formation.

The components of H_iE can be estimated both experimentally and theoretically (Baldwin, 1995). Quantitatively, H_dE represent the greatest proportion of H_iE (10-20% of ME_m; Baldwin and Smith, 1974). Although effects of nutrition and physiological state can explain variation in the components of H_iE, these components are not typically considered individually or modeled as factors affecting the utilization ME in the pig. Approaches have been developed to model energy utilization in the pig containing greater mechanistic elements (Birkett and de Lange, 2001a,b,c; van Milgen et al., 2001; van Milgen, 2002). Although these models provide greater power in defining energy utilization, conventional broad-based application is limited. Therefore a commonly used model to partition ME is that of Kielanowski (1965):

$$MEI = ME_m + (1 / k_p) \text{ PEG} + (1 / k_f) \text{ LEG} \quad \text{(Eq. 1-14)}$$

where MEI = ME intake, ME_m = ME for maintenance, k_p and k_f are the partial efficiencies of ME use for protein (PEG) and lipid energy gain (LEG), respectively.

Discussion of k_p and k_f will be presented subsequently (see Growth in the section Physiological States below).

Maintenance

Fasting heat production represents the greatest portion of maintenance (ME_m):

$$ME_m = FHP + H_iE\text{(maintenance)} \quad \text{(Eq. 1-15)}$$

The methodology and assumptions used to estimate FHP were previously described (see Net Energy in the section Partitioning of Energy above). In general, FHP and ME_m are expressed as a function of an allometric equation related to BW (aW^b). Numerous reports have reviewed and estimated FHP and ME_m for pigs (Tess et al., 1984a; Noblet et al., 1994, 1999; de Lange et al., 2006). There has been significant debate and variation in the appropriate exponent (b) for the allometric equation describing maintenance. Historically the exponent of 0.75 had been used to describe ME_m (106 kcal ME/kg $BW^{0.75}$, NRC, 1998; 109 kcal ME/kg $BW^{0.75}$, ARC, 1981). However, there is compelling evidence suggesting that the exponent function is significantly less than 0.75 (ranging from 0.54 to 0.75; Tess, 1981). It has been proposed that the appropriate exponent is closer to 0.60 (Noblet et al., 1999). Designation and use of the appropriate exponent function is critical in terms of estimating maintenance energy values and k_p and k_f (Noblet et al., 1999; de Lange and Birkett, 2005). Fasting heat production estimates of 137 kcal/kg $BW^{0.60}$ (van Es, 1972); 179 kcal/kg $BW^{0.60}$ (Noblet et al., 1994); and 167 kcal/kg $BW^{0.60}$ (van Milgen et al., 1998) have also been reported. It is generally accepted that NE_m = FHP + energy allocated for physical activity (van Milgen et al., 2001).

A number of factors affect FHP (ME_m; Baldwin, 1995; Birkett and de Lange, 2001b). Previous energy and nutrient (protein) intake affect FHP. Increased energy and protein intake (Koong et al., 1983) increase FHP due mainly to increased gastrointestinal tract and liver mass (Critser et al., 1995). It is estimated the gastrointestinal tract and liver can account for as much as 30% of FHP respectively (Baldwin, 1995).

In general, metabolic BW ($BW^{0.75}$) is used to scale FHP and ME_m for sows. The ME_m ranges from 95 to 110 kcal/kg $BW^{0.75}$ (Dourmad et al., 2008). No evidence exists suggesting that ME_m differs between primiparous and multiparous sows. A value of 105 and 110 kcal ME/kg $BW^{0.75}$ has been proposed to express ME_m in gestating and lactating sows, respectively (Dourmad et al., 2008). Presently, the values for ME_m used in the gestation and lactation models (Chapter 8, Gestating Sow Model and Lactating Sow Model sections) are 100 and 110 kcal ME/kg $BW^{0.75}$.

There does not seem to be data supporting differences in FHP or ME_m between barrows, gilts, and boars (NRC, 1998; Noblet et al., 1999). However, variation in FHP and ME_m has been shown to differ among populations that exhibit different rates of lean growth (Noblet et al., 1999). Therefore, based on lean-gain estimates (potentials), it could be debated that maintenance requirements are greater for gilts and boars (greater protein accretion). The practice of assuming constant FHP or ME_m among populations, lines, and sexes may not be appropriate; however, adjustments to FHP (estimating NE) or allotting MEI have to be done judiciously. In general, ME_m for growing-finishing pigs ranges from 191 to 216 kcal/kg $BW^{0.60}$ (mean = 197 kcal/kg $BW^{0.60}$; Birkett and de Lange, 2001c).

Maintaining Body Temperature

Previous discussions have focused on estimates of energy expenditure (maintenance) in thermoneutral environments. Deviation below the lower critical temperature (LCT) and above the upper critical temperature (UCT) can affect pig heat production/loss and MEI. Therefore, average daily feed intake (ADFI) is increased at $T < LCT$ and decreased at $T > UCT$. The majority of studies have focused on temperatures above UCT. The responses of feed intake to ambient temperature are affected by the interaction of the pig and environment (e.g., air temperature, wind speed, pen/housing materials, housing density; see Curtis, 1983, for a review). In addition, energy density can affect voluntary intake (Stahly and Cromwell, 1979, 1986). The interaction of energy density and feed intake above UCT and below LCT is related to H_iE. Specifically, high-fiber diets produce greater H_iE and can help generate heat at $T < LCT$, while lipid-supplemented diets produce less H_iE and can help with heat loads at $T > UCT$.

Growing Pigs

The LCT and UCT are affected by BW (Holmes and Close, 1977; Noblet et al., 2001; Meisinger, 2010) and MEI (Bruce and Clark, 1979; Whittemore et al., 2001). For the 60-kg pig, increasing the intake from maintenance to 3 × maintenance decreased LCT approximately 6-10°C (Holmes and Close, 1977). Verstegen et al. (1982) estimated that during their growth period, from 25 to 60 kg, pigs needed an additional 25 g of feed/day (80 kcal of ME/day) to compensate for each 1°C below LCT. During the finishing period, from 60 to 100 kg, pigs require an additional 39 g of feed/day (125 kcal of ME/day) for each 1°C below LCT. At temperatures below LCT, ME_m is required for thermogenesis (where ME for thermogenesis (kcal/day) = $0.07425 \times (LCT - T) \times ME_m$).

The majority of studies have demonstrated a 10-30% decrease in ADFI (MEI) as ambient temperature increased from approximately 19 to 31°C (Collin et al., 2001; Quiniou et al., 2001; Le Bellego et al., 2002; Renaudeau et al., 2007). Le Dividich et al. (1998) estimated that feed intake can be decreased up to 80 g/°C per day. The effects of temperature on feed intake interact with BW (Close, 1989; Quiniou et al., 2000). Quiniou et al. (2000) expressed voluntary intake (VFI) as a function of BW and ambient temperature (T):

$$\begin{aligned} \text{VFI (g/day)} = &-1{,}264 + (73.6 \times BW) \\ &- (0.26 \times BW^2) \\ &+ (117 \times T) \\ &- (2.40 \times T^2) \\ &- (0.95T \times BW), \end{aligned} \quad \text{(Eq. 1-16)}$$

where temperature range, 12-29°C; BW range, 63-74 kg.

Gestation

The LCT for sows individually housed ranges from 20 to 23ºC (Noblet et al., 1989). The LCT may be as great as 6ºC lower for group vs. individually housed sows (Verstegen and Curtis, 1988). Because most gestating sows are limit fed, temperatures above UCT are not commonly considered relative to ME_m or MEI. However, temperatures below the LCT increase MEI required for thermogenesis. The additional ME required to maintain body temperature ranges from 2.5 to 4.3 kcal ME/$kg^{0.75}$ per Celsius degree (Noblet et al., 1997).

Lactation

Typically, there are not issues related to temperatures below LCT in lactating sows. The UCT for lactating sows ranges between 18 and 22ºC (Black et al., 1993). Metabolizable energy intake is decreased at ambient temperatures above UCT. The decrease in MEI in lactating sows with increasing ambient temperature is variable. Quiniou and Noblet (1999) showed that the decrease in MEI was temperature dependent (0.33 Mcal ME per Celsius degree per day for 18-25ºC; 0.76 Mcal ME per Celsius degree per day for 25-27ºC; 2.37 Mcal ME per Celsius degree per day for 18-25ºC).

Activity

Physical activity also influences heat production. Petley and Bayley (1988) measured the heat production of pigs running on a treadmill and reported that heat production of the exercised pigs was 20% greater than that of control animals. Close and Poorman (1993) calculated that the additional expenditure of energy by growing pigs for walking was 1.67 kcal of ME/kg of BW for each kilometer. Noblet et al. (1993) measured the increase in heat production associated with standing by sows as 6.5 kcal of ME/kg of $BW^{0.75}$ for each 100 minutes. This figure was similar to reports by Hornicke (1970) of 7.2, by McDonald et al. (1988) of 7.1, by Susenbeth and Menke (1991) of 6.1, and by Cronin et al. (1986) of 7.6 kcal/kg of $BW^{0.75}$ for each 100 minutes. Noblet et al. (1993) also determined that the energy cost of consuming feed was 24-35 kcal of ME/kg of feed consumed.

PHYSIOLOGICAL STATES

Although it is generally accepted that energetic transformations at the chemical reaction level define overall energy use and energetic efficiency mechanistically, the required level of complexity is prohibitive relative to defining useable nutrient requirement estimates. In addition, many parameters needed to describe mechanistic models are not defined for the various swine physiological states in the context of the nutrient and energy requirements presented herein (growth, pregnancy, lactation). This is best exemplified in the adaptation of the current computer model representing the pig's response to energy intake (see Chapter 8).

Growth

The determinants of energy needs for growth are a function of BW (maintenance) and the proportion of protein and lipid in gained tissues. Therefore, the efficiency of energy (ME) use for growth (above maintenance) is a function of the energetic efficiency of ME for protein (k_p) and lipid (k_f) deposition (previously described in the section Components of Heat Production). The partial efficiencies of ME use for protein deposition range from 0.36 to 0.57 (Tess et al., 1984b), and for lipid deposition the estimates range from 0.57 to 0.81 (Tess et al., 1984b). Alternatively, the ME cost per gram of protein and lipid deposition is estimated at 10.6 and 12.5 kcal/g, respectively (Tess et al., 1984b; NRC, 1998).

Birkett and de Lange (2001c), using a model of simplified nutrient pathways, predicted k_p and k_f were in the range of 0.47-0.51 and 0.66-0.72, respectively. These estimates were affected by diet composition (see below) and the composition/pattern of growth. Whittemore et al. (2001) determined that k_p was affected by the substrate used for protein synthesis and rate and amount of protein deposited. Likewise, the overall efficiency of ME used for lipid deposition (k_f) is dependent on the composition of lipid deposited, adipose tissue turnover, and the profile of lipid precursor substrates (Birkett and de Lange, 2001c; Whittemore et al., 2001).

The composition of ME (i.e., dietary protein, starch, and lipid) affects the energetic efficiency of ME utilization. Noblet et al. (1994) estimated the efficiency of ME conversion to NE (k) of 0.58, 0.82, and 0.90 for protein, starch, and lipid, respectively. These values agree with those estimated by van Milgen et al. (2001; 0.52, 0.84, and 0.88, for protein, starch, and lipid, respectively). Overall, using a variety of mixed diets, k values ranged from 0.70 to 0.78 (Noblet et al., 1994; van Milgen et al., 2001; Noblet and van Milgen, 2004).

Intake of ME is a critical factor in determining growth rate. Concepts on control and regulation of feed intake have been thoroughly reviewed elsewhere (NRC, 1987; Kyriazakis and Emmans, 1999; Ellis and Augspurger, 2001; Torrallardona and Roura, 2009). Bridges et al. (1986) proposed the following equation form to predict MEI:

$$MEI = a \times \{1 - \exp[-\exp(b) \times BW^c]\} \quad \text{(Eq. 1-17)}$$

This equation can be parameterized (a, b, and c values) to predict MEI for different sexes and pigs with differing genetic capacities for growth (Schinckel et al., 2009).

Pregnancy

Feeding during gestation is critical to the development and growth of the fetus and corresponding tissues (placenta, uterus, and mammary tissue) and deposition of maternal lipid and protein. The nutrient and energy requirements for the gestating sow have been outlined in several key reviews (ARC, 1981; Aherne and Kirkwood, 1985; Dourmad et al., 1999, 2008; Boyd et al., 2000; Trottier and Johnson, 2001). Typically, because gestating sows are limit fed, feed intake is not predicted.

Increased energy intake during late gestation can positively affect fetal growth and maternal weight gain; however, potential problems with excessive energy intake can occur and may negatively affect subsequent lactational performance. Increased feed intake during gestation has been associated with decreased energy intake and sow weight loss during the subsequent lactation (Williams et al., 1985; Weldon et al., 1994). Previously, a daily MEI of 6.0 Mcal/day was identified (ARC, 1981; Whittemore et al., 1984; NRC, 1998) to maximize fetal growth and maternal gain during pregnancy. This MEI intake is equivalent to feed intakes of 1.6-2.4 kg/day depending on diet ME density. Litter size and birth weights have increased since the last revision of the NRC report (NRC, 1998); therefore, MEI required may be as high as 6.5 Mcal/day, but ought to be adjusted relative to litter size, mean birth weight, stage of lactation, and sow parity.

Weight gain during pregnancy is a result of maternal protein and lipid deposition, and conceptus gain. Energy (ME) required for each of the aforementioned components can be determined from the estimates of the efficiency of ME use for maternal gain (k_p for protein and k_f for lipid) and conceptus growth (k_c). Likewise, maternal protein and lipid can be mobilized to support the developing fetus and tissues (k_r). The latter instance is usually the exception and would likely be transitory, resulting from inadequate energy or nutrient intake during late pregnancy if feed intake is applied during the entire gestation period. Values for k_p and k_f have been estimated (0.60 and 0.80, respectively; Noblet et al., 1990). The k_r estimate (0.80) is similar to k_f and implies that the majority of energy mobilized by the sow to support pregnancy would be from adipose (Noblet et al., 1990; Dourmad et al., 2008).

Although tissues associated with fetal growth have been defined (fetus, placenta, fluids, uterus; Noblet et al., 1985), k_c estimates typically refer to the products of the conceptus (fetus + placental + fluids). With this definition of the conceptus, k_c is calculated to be approximately 0.50 (Close et al., 1985; Noblet and Etienne, 1987); however, if the energy costs associated with maintaining the uterus are not allocated to the sows' maintenance requirement the estimated efficiency is reduced (k_c = 0.030; Dourmad et al., 1999). The energy for conceptus growth (note that units are expressed in kilojoules [kJ]; to express in kilocalories, an exponential conversion is required and the resulting term can be converted from kilojoules to kilocalories) is related to the stage of gestation and expected litter size and can be estimated from:

$$\ln (ER_c) = 11.72 - 8.62 \exp (-0.0138\, t + 0.0932\, LS);$$
(Noblet et al., 1985) (Eq. 1-18)

where ln (ER_c) is the natural logarithm of energy retained in the conceptus, t = gestation length (days), and LS = expected litter size (number).

For a litter size of 12 pigs, ER_c would be equivalent to 15.2 Mcal deposited in the conceptus or 1.3 Mcal/pig. The ME required for conceptus growth would be ER_c/k_c.

Lactation

Changes in energy balance during lactation can have potential long-term effects on sow reproduction and longevity (Dourmad et al., 1994). Energy requirements for the lactating sow are defined by MEI for maintenance (potentially affected by temperature and activity) and milk production. In addition, because energy intake is often not sufficient to support milk production, and sows will mobilize body lipid and protein stores to support lactation, it is desirable to maximize feed intake in lactating sows. The metabolic and reproductive consequences of limited feed intake and concomitant tissue mobilization are heightened in younger vs. older sows (Boyd et al., 2000).

The ME_m estimated previously for lactating sows (NRC, 1998) was 106 kcal ME/$W^{0.75}$, which was the same as described for gestating sows. Studies have indicated that ME_m for lactating sows is 5-10% greater than during pregnancy (Noblet and Etienne, 1986, 1987). Noblet et al. (1990) determined that ME_m = 110 kcal/$W^{0.75}$ for lactating sows. This estimate is 10% greater compared to the ME_m for pregnancy (100 kcal/$W^{0.75}$; see Pregnancy section).

The genetic potential of the sow to produce milk as indicated via litter growth rate is the primary determinant of lactational energy needs. The energy content associated with milk production can be estimated from piglet growth rate and the number of pigs in the litter (Noblet and Etienne, 1989; NRC, 1998):

$$\text{Milk Energy (GE, kcal/day)} = (4.92 \times ADG) - (90 \times LS)$$
(Eq. 1-19)

where ADG = average daily gain (litter, g), and LS = number of pigs per litter. Thus, using a standardized lactation milk production curve (Whittemore and Morgan, 1990), it is possible to calculate daily energy output.

The efficiency (k_m) of conversion of ME to milk energy ranges from 0.67 to 0.72 (Verstegen et al., 1985; Noblet and Etienne, 1987). Previously (NRC, 1998), k_m was assumed to be 0.72 and this is consistent with the model described by Dourmad et al. (2008). Presently (see Chapter 8, Partitioning of ME Intake section), k_m is equal to 0.70 in the lactating sow model.

The response of MEI vs. day of lactation can be described using a nonlinear equation approach described by Schinckel et al. (2010). Dietary MEI is rarely sufficient to support the energy need of milk production in the lactating sow, and thus, sow body tissue is mobilized to support energy (and nutrients) required for milk production. As expected, the efficiency of using body tissue(s) to support the energy needs of milk (k_{mr}) is greater than k_m. The conversion of body tissue energy to milk energy ranges from 0.84 (de Lange et al., 1980) to 0.89 (Noblet and Etienne, 1987; NRC, 1998).

Developing Boars and Gilts

Typically, boars and gilts are given ad libitum access to diets until selected as breeding animals at about 100 kg BW to allow evaluation of the potential growth rate and lean gain. After the animals are selected for the breeding herd, energy intake is restricted to achieve the desired weight at the time the animals are used for breeding (Wahlstrom, 1991).

Sexually Active Boars

The energy requirement of the working boar is the sum of the energy required for maintenance, mating activity, semen production, and growth. Kemp (1989) reported that the heat production associated with the collection of semen when mounting a dummy sow was 4.3 kcal of DE/kg of $BW^{0.75}$. Close and Roberts (1993) estimated the energy required for semen production from the average energy content of each ejaculation (62 kcal of DE) and an estimate of the efficiency of energy utilization (0.60). The energy required was 103 kcal of DE per ejaculation.

Immunization Against Gonadotropin Releasing Hormone

Recently, chemical castration of intact male pigs using immunizations against gonadotropin releasing hormone has been approved in several countries to control off-flavored meat related to boar taint from entire male pigs. Until the second immunization injection (4-6 weeks before harvest), immunized intact males maintain growth performance and protein deposition similar in magnitude to non-immunized intact males. After the second immunization, circulating hormone concentrations and profiles resemble those of barrows, and performance transitions over a 7- to 10-day period to similar levels achieved by barrows. While response to this immunization has been shown to vary among studies, during the 4- to 5-week period after the second immunization, it is typical for respective daily feed intake and BW gains to be 18% and 13% higher in immunized males than intact males, while back fat thickness at the end of this period is typically 17% higher in immunized males (Bonneau et al., 1994; Dunshea et al., 2001; Metz et al., 2002; Turkstra et al., 2002; Zeng et al., 2002; Oliver et al., 2003; Pauly et al., 2009; Fàbrega et al., 2010). This response suggests that protein gain is slightly reduced when entire males are immunized and that most of the additional energy intake is used for lipid deposition.

Feeding Ractopamine

The effects of dietary ractopamine administration are described in Chapter 10 (Nonnutritive Feed Additives). Ractopamine administration can have specific and independent effects on protein and lipid metabolism that is reflected by decreased MEI per unit of growth (NRC, 1994; Schinckel et al., 2006). The decrease in MEI associated with ractopamine is a function of BW gain during the ractopamine supplementation period and the dietary concentration of ractopamine. Feeding ractopamine will increase body protein deposition and, therefore, reduce the amount of energy available for lipid deposition. The impact of ractopamine on the partitioning between body protein and lipid deposition will vary with dietary level and the duration of feeding ractopamine (see section in Chapter 8 on Impacts of Feeding Ractopamine and Immunization of Entire Males Against Gonadotropin Releasing Factor on Nutrient Partitioning).

MODELING ENERGY UTILIZATION—THE CONCEPT OF EFFECTIVE METABOLIZABLE ENERGY

Various approaches have been developed with the objective of defining a mathematical description of energy requirements for growing and reproducing pigs (Black et al., 1986; Pomar et al., 1991; NRC, 1998; van Milgen et al., 2008). The calculation rules to represent energy utilization in the new model are explained in detail in Chapter 8. A key concept relative to representing energy use in the models is effective ME and will be described here.

In concept, current NE systems are more accurate than ME and DE systems in representing the impact of dietary energy source (e.g., starch, fiber, protein, fat) on the efficiency of using dietary energy for supporting animal performance (Eqs. 1-7 to 1-10). However, in these NE systems, the purpose for which energy is used by pigs is not considered explicitly. For example, when the NE content in a diet for growing pigs is established, it is assumed that the relative use of energy for protein and lipid gain and for body maintenance functions does not differ between groups of pigs, even when these groups of pigs vary in rate and composition of BW gain. Yet it is known that the marginal efficiency of using ME for lipid gain is substantially higher than using ME for protein gain and body maintenance functions (Eq. 1-14). In more accurate energy systems, both the dietary energy source and the use of energy by pigs are considered. The latter is accommodated in models that represent the utilization of energy-yielding nutrient in pigs explicitly (Birkett and de Lange, 2001a,b,c; van Milgen et al., 2001). An important limitation of such more mechanistic models is that the (net) energy values of ingredients and nutrients are not constant and are influenced by the animal's performance level, which is difficult to account for in diet formulation.

As a compromise between current NE systems and more mechanistic energy utilization models, the concept of effective ME is adopted in the models that are presented in this publication. In this approach, the effective ME contents of diets are calculated from the diet NE content using fixed conversion efficiencies for either starting pigs (5 to 25 kg BW; 1/0.72), growing-finishing pigs (25 to 135 kg BW; 1/0.75), or sows (1/0.763) . These fixed conversion efficiencies are established from calculated NE and ME contents of corn and dehulled solvent-extracted soybean meal-based reference diets that are assumed to be equivalent to diets that have been used for deriving marginal efficiencies of using ME for the various body functions. These corn and dehulled solvent-extracted soybean meal-based diets were formulated to contain 3,300 kcal ME/kg, small and variable amounts of added fat, 0.1% added lysine·HCl, 3% added vitamins and minerals, and to meet the typical lysine requirements for these three categories of pigs. In the models, effective ME is used to represent partitioning of energy intake between requirements for maintenance, protein, and lipid energy gain, energy gain in products of conception, and milk energy output. When using the concept of effective ME, the effective ME content is higher than the actual ME contents in diets that have low heat increment of feeding (e.g., diets with large amounts of added fat) and lower than the actual ME contents in diets with high heat increment of feeding (e.g., diets that contain high levels of fibrous ingredients). In a similar manner, fixed conversions are used when converting (effective) diet DE content to effective ME content (0.96 for starting pigs, 0.97 for growing-finishing pigs, and 0.974 for sows). In this text and when describing the models, the terms "ME" and "effective ME" are used interchangeably. In the tables of feed ingredient composition (Chapter 17), there is no differentiation of energy for different classes of swine within ingredient (i.e., for each ingredient one set of energy values is used for starting pigs, growing-finishing pigs, and sows). The amount of published data was considered insufficient to justify differentiation by stage of production.

The most accurate means to predict the pigs' response to energy intake is to use diet NE contents as model inputs and use the model to generate estimates of effective ME for predicting the pig's response to energy intake. When diet DE or diet ME contents are used as model inputs, the impact of the contribution of individual energy-yielding nutrient on energetic efficiencies are ignored.

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2

Proteins and Amino Acids

INTRODUCTION

The main goal of this chapter is to describe the approaches used to determine the amino acid requirements of starting pigs, growing-finishing pigs, sows, and boars. Classification, sources, and metabolism of amino acids are briefly discussed, followed by a review of published estimates of amino acid requirements. The main determinants of amino acid requirements of growing-finishing pigs, gestating sows, and lactating sows are described. In the final section, estimates of amino acid requirements of nursery pigs and breeding boars are presented.

PROTEINS

Proteins are composed of amino acids, and analyzed nitrogen contents are generally used to estimate crude protein (CP) contents in feed. The product of the nitrogen content of feed ingredients and 6.25 gives the CP content, implying that nonprotein nitrogen contributes to CP, and hence the term "crude protein." The factor of 6.25 is derived from the assumption that the average nitrogen content of protein is 16 g of nitrogen per 100 g of protein. However, nitrogen content of protein varies in different foods. The nitrogen content in grams per 100 g of protein for the following foods is: barley, 17.2; corn, 16.1; millet, 17.2; oats, 17.2; rice, 16.8; rye, 17.2; sorghum, 16.1; wheat, 17.2; peanut, 18.3; soybean, 17.5; egg, 16.0; meat, 16.0; and milk, 15.7. Functionally, dietary proteins supply amino acids that are the essential nutrients used by the body. Quantitatively, protein is an expensive nutrient in the diets of pigs and its conversion into animal tissues requires digestion, absorption, and postabsorptive metabolism of the derived amino acids. The adequacy and quality of dietary protein depends on the capability of the protein to provide amino acids in correct amounts and proportions.

ESSENTIAL, NONESSENTIAL, AND CONDITIONALLY ESSENTIAL AMINO ACIDS

The 20 primary amino acids that occur in proteins (Table 2-1) are conventionally classified as dietary essential and nonessential. An essential amino acid is one that cannot be synthesized by pigs from materials ordinarily available in cells at a rate matching the demands for productive functions including maintenance, normal growth, and reproduction. The term "ordinarily available" is important because a number of nutritionally essential amino acids, such as methionine, phenylalanine, and the branched-chain amino acids, can be synthesized by transamination of their analogous α-keto acids, but these keto acids are not normally part of the diet and thus are not ordinarily available to the cells. The term "at a rate" is also important because there are situations where the rate of synthesis of an amino acid can be limited by the availability of appropriate quantities of metabolic nitrogen. Arginine, cysteine, glutamine, glycine, proline, and tyrosine are important in this regard because under some conditions, rates of utilization are greater than

TABLE 2-1 Essential, Nonessential, and Conditionally Essential Amino Acids

Essential	Nonessential	Conditionally Essential
Histidine	Alanine	Arginine
Isoleucine	Asparagine	Cysteine
Leucine	Aspartate	Glutamine
Lysine	Glutamate	Proline
Methionine	Glycine	Tyrosine
Phenylalanine	Serine	
Threonine		
Tryptophan		
Valine		

rates of synthesis, such that these amino acids can be classified as conditionally essential (Reeds, 2000). Typically, swine have sufficient capacity for synthesis of conditionally essential amino acids. Thus, most of the emphasis in swine nutrition is on essential amino acids and total nitrogen, as a substrate for synthesis of nonessential and conditionally essential amino acids.

Using a restrictive metabolic definition to classify amino acids as essential based on the animal's capacity for endogenous synthesis, Reeds (2000) articulated that several essential amino acids can be synthesized from precursors that are structurally very similar to these amino acids. Examples include methionine (which can be synthesized both by transamination of its keto acid analog and by remethylation of homocysteine), and leucine, isoleucine, valine, and phenylalanine (which can be synthesized from branched-chain keto acids). Therefore, using this metabolic definition, the only truly essential amino acids are threonine and lysine (and perhaps tryptophan). A metabolic definition of a truly nonessential amino acid is one that can be synthesized de novo from a non-amino acid source of nitrogen, such as ammonium ions, and an appropriate carbon source such as an α-keto acid. Thus strictly speaking, glutamic acid and serine are the only truly metabolically nonessential amino acids.

Rates of arginine synthesis from glutamine during the early stages of growth are inadequate to meet growth needs. Consequently, the diets of growing swine have to contain a source of arginine. Furthermore, the amount of arginine supplied by a corn-soybean meal–based diet is also inadequate for optimal growth of very young pigs (Kim et al., 2004; Wu, 2009). In contrast to earlier work by Easter and Baker (1977) in which purified diets were used, synthesis of arginine may be insufficient to meet gestational needs and the demands of lactation, as indicated by a more recent study where supplementation of a corn-soybean meal–based diet with 0.83% arginine increased the number and total litter weight of live-born pigs (Mateo et al., 2007).

Cysteine can satisfy approximately 50% of the need for total sulfur amino acids (Chung and Baker, 1992a; Lewis, 2003; Ball et al., 2006), and in this way can reduce the need for methionine because it can be synthesized from methionine. In the absence of cysteine, the total need for sulfur amino acids can be satisfied by methionine, although there may be some improvement in pig performance when at least a portion of the sulfur amino acid requirement is provided by cysteine (Lewis, 2003). Cysteine is also important for the immune system because it is used for glutathione synthesis.

Phenylalanine can meet the total requirement for phenylalanine and tyrosine (aromatic amino acids) because it can be converted to tyrosine. Tyrosine can satisfy up to about 50% of the total need for these two amino acids (Robbins and Baker, 1977).

Less than one-third of the dietary glutamine intake appears in portal blood because of extensive intestinal utilization (Boelens et al., 2003; Stoll and Burrin, 2006). Glutamine also promotes cell proliferation and exerts differential cytoprotective effects in response to nutrient deprivation, oxidative injury, stress, and immunological challenge (Rhoads and Wu, 2009).

The synthesis of proline is dependent on intestinal metabolism and uses amino acid precursors of dietary rather than systemic origin (Murphy et al., 1996; Stoll et al., 1998; Reeds, 2000). Alterations in intestinal metabolism can have a critical bearing on the ability of the organism to synthesize proline. Wu (2009) suggested that < 60% of the requirement of growing pigs for dietary proline is met by proline that appears in portal blood, implying that > 40% is synthesized.

In summary, although some amino acids (essential) have to be provided in swine diets and others (nonessential) are never required in the diet provided there is a sufficient source of nitrogen, the need for others (conditionally essential) depends on dietary and physiological conditions. In Table 2-1, the 20 primary amino acids are divided into the three categories.

AMINO ACID SOURCES

The primary ingredients in most of the diets of swine are cereal grains, such as corn, sorghum, barley, or wheat, and they commonly provide 30-60% of the total amino acid requirements. Because cereal grains are notoriously deficient in some essential amino acids, other sources of protein, such as soybean meal, are provided to ensure adequate amounts of, and a proper balance among, the essential amino acids. Individual amino acids (produced by fermentation or chemical synthesis) may also be used as supplements to increase intakes of specific amino acids.

Adequate dietary intakes of essential amino acids will depend on the feed ingredients contained in the diets. Feed ingredients that have an amino acid pattern relatively similar to that required by pigs to meet maintenance and production needs are desirable. Mixtures of feed ingredients in which the amino acid pattern in one complements the pattern in another will meet the essential amino acid requirements at lower dietary nitrogen concentrations than feed ingredients with a less desirable amino acid pattern. This is important if one of the goals is to minimize nitrogen excretion. The judicious use of supplements of individual amino acids in diet formulation will reduce dietary protein concentrations and thereby reduce nitrogen excretion into the environment. Furthermore, amino acid imbalances may be prevented and the metabolic costs of amino acid deamination and excretion of urea are minimized.

In all cases, the requirements listed in this publication refer to the L isomer, the form in which most amino acids occur in plant and animal proteins. When provided in synthetic form, DL-methionine can replace the L form in meeting the need for methionine (Reifsnyder et al., 1984; Chung and Baker, 1992c; Lewis, 2003), although there is evidence that the D form may be used less effectively than the L form by very young pigs (Kim and Bayley, 1983). Estimates of the biological activity of D-tryptophan vary from 60 to 100% of that of L-tryptophan for the growing pig (Baker et al., 1971; Arentson and Zimmerman, 1985; Kirchgessner and Roth, 1985; Schutte et al., 1988). The activity of the D form may depend on the proportion of D- and L-tryptophan in the diet and on whether the amino acid is added as D-tryptophan or as DL-tryptophan (the racemic mixture). D-Lysine and D-threonine are not used by any of the animal species that have been tested because these two amino acids do not undergo transamination reactions and thus their α-keto acids are not converted to L isomers, which explains why lysine and threonine are truly essential amino acids. The values of the D forms of other essential amino acids for the pig are not known.

Commercial feed-grade sources of individual amino acids produced by fermentation include L-lysine·HCl (98.5% pure = 78.8% lysine activity), L-threonine (98.5% pure), and L-tryptophan (98.5% pure). Commercial feed-grade sources of synthetic amino acids include DL-methionine (99% pure) and DL-methionine hydroxy analog (a liquid that contains 88% methionine hydroxy analog). Estimates of the biological efficacy of the various sources of methionine vary considerably. In poultry, where more than 70 papers (comprising approximately 500 experiments) and at least three meta-analyses have been published, there is still disagreement among researchers. In addition, some amino acids can be purchased together in a mixture (e.g., lysine and tryptophan), and others are available in a liquid form (e.g., lysine). To simplify the terminology, the term "crystalline" is used to designate individual amino acids produced by either fermentation or synthesis.

AMINO ACID ANALYSIS

The analysis of amino acids forms an essential basis for the current state of knowledge on protein nutrition. Advances in knowledge of protein nutrition are dependent on the accurate and precise quantification of nitrogen and amino acids in foods, feeds, tissues, body fluids, and digesta. The procedures used for amino acid analyses may cause variations in published estimates of amino acid requirements. Methods of sample preparation (hydrolysis of intact proteins or protein precipitation for free amino acids) and separation of the amino acids for quantification are crucial in this regard and were discussed by Williams (1994) and Kaspar et al. (2009). Determined contents of the sulfur amino acids and tryptophan in dietary ingredients, in particular, vary considerably. Methionine and cysteine undergo oxidation to multiple derivatives, and controlled oxidation of methionine to methionine sulfone and of cysteine to cysteic acid is carried out with performic acid before hydrochloric acid hydrolysis. The relatively low concentration of tryptophan in most feed ingredients and its partial destruction during standard hydrochloric acid hydrolysis both present particular challenges. For these reasons, special precautions, including hydrolysis with barium hydroxide, sodium hydroxide, or lithium hydroxide, or protection against oxidation in acid, are required in sample preparation. More detailed information was given by Fontaine (2003). Finally, the time required to hydrolyze peptide bonds in acid varies with the amino acid. For example, the time required to fully hydrolyze peptide bonds of isoleucine and valine is longer than for other amino acids, and extended hydrolysis times are usually recommended, whereas prolonged hydrolysis time can result in destruction of threonine and serine. Curvilinear mathematical models from multiple-hydrolysis-time procedures allow accurate prediction of amino acids when compared with the conventional 24-hour hydrolysis.

MEANS OF EXPRESSING AMINO ACID REQUIREMENTS

Units

The requirements of pigs for amino acids may be expressed in terms of dietary concentration, amounts per day, amounts per unit of metabolic body weight ($BW^{0.75}$), amounts per unit of protein accretion, or amounts per unit of dietary energy. When the amino acid requirements are expressed in terms of dietary concentration, they increase as the energy density of the diet increases. Thus, at higher or lower energy densities than those found in standard grain-soybean meal diets, amino acid requirements (expressed as a percentage of the diet) may need to be adjusted upward or downward, respectively. The impact of variation in energy intake on amino acid requirements has to be considered as well. When energy intakes differ from typical levels, it is suggested that amino acid requirements are based on constant dietary amino acid to energy ratios for young pigs when energy intake is limiting body protein deposition. Also, in situations, especially commercial practice, where energy intake is lower than genetic capacity, it is suggested that amino acid requirements are based on constant dietary amino acid to energy ratios.

Bioavailability

Most dietary proteins are not fully digested and the amino acids are not fully absorbed. Furthermore, not all absorbed amino acids are metabolically available. Diets vary considerably in the proportions of their amino acids that are biologically available. For example, the amino acids in some proteins such as milk products are almost fully bioavailable, whereas those in other proteins such as certain plant seeds are much less so (Lewis and Bayley, 1995; Moehn et al., 2007; Adeola, 2009). As a consequence, a careful assessment of the bioavailability of each of the dietary amino acids in proteins is critical for evaluating the dietary protein values of feed ingredients for pigs and the expression of amino acid requirements. Expressing amino acid requirements in terms of bioavailable requirements is, therefore, desirable. This means that the bioavailable amino acid contents of the ingredients being considered in formulating swine diets have to be known. Growth assays using slope-ratio methodology have been used to determine relative bioavailability of amino acids in feeds for pigs (Batterham, 1992; Kovar et al., 1993; Adeola et al., 1994; Adeola, 2009) with the response to increased concentrations of a single amino acid from a test ingredient being expressed relative to the response obtained to feeding increasing levels of crystalline amino acid.

Because slope-ratio assays are tedious, costly, and the estimated bioavailabilities may not be additive in mixtures of feed ingredients, amino acid digestibility is routinely used for estimation of bioavailability of amino acids. Furthermore, slope-ratio assays present substantial challenges in controlling for the effects of dietary components of the test ingredients other than the limiting amino acid, and, as a consequence, result in high variation. The primary method to determine digestibility of amino acids has been to measure the proportion of a dietary amino acid that has disappeared from the small intestine by recovering the digesta at the terminal ileum. The ileal digesta analysis method was developed to correct for amino acids that disappear from the hindgut—due to microbial fermentation—and that are of no value to the animal. A certain proportion of the undigested protein entering the hindgut is fermented by hindgut microflora and the remainder is excreted in feces. Microflora nitrogen makes up 62-76% of total fecal nitrogen. Microflora activity in the hindgut is dependent on the amount of available fermentable carbohydrate. In the original study by Zebrowska (1978), intact or hydrolyzed casein infused in the distal part of the ileum of pigs fed a protein-free diet was digested and absorbed; however, the absorbed substrates (mostly ammonia and some amines) were rapidly and almost completely excreted in urine. Further studies (reviewed by Sauer and Ozimek, 1986) also showed that protein or amino acids infused into the hindgut make little or no contribution to the protein status of the animal. However, under certain dietary conditions when nitrogen may be limiting for the synthesis of the nonessential amino acids, nitrogen absorbed from the hindgut could contribute by sparing the utilization of essential amino acids (Metges, 2000). In addition, it has been shown that amino acids synthesized by the enteric microbial population can contribute to whole-body amino acid homeostasis in the pig by meeting the equivalent of amino acid requirement estimates for maintenance (Torrallardona et al., 2003a,b), but it appears that the ileum may be the site for both synthesis and absorption of microbial amino acids (Torrallardona et al., 2003b). It has also been shown that enteric fermentation prior to the distal ileum can contribute to amino acid catabolism (Libao-Mercado et al., 2009), reducing the amino acid supply to the host. These observations indicate that the impact of enteric microbial populations on the net amino acid supply to the host remains to be quantified accurately.

Sauer and Ozimek (1986) reviewed evidence for the superiority of ileal over fecal digestibility of amino acids from studies in which there were higher correlations between both daily gain and feed efficiency with ileal nitrogen digestibility than with nitrogen digestibility measured from fecal collection. Values determined in this manner are termed ileal digestibility rather than bioavailability because amino acids are sometimes absorbed in a form that cannot be fully used in metabolism. Measures of digestibility are based on amino acid disappearance from the digestive tract and do not reflect the form in which amino acids are absorbed. For feedstuffs exposed to excess heat treatment, however, ileal digestibility values overestimate bioavailabilities of lysine, threonine, methionine, and tryptophan as determined by growth assays using slope-ratio (Batterham, 1994; Van Barneveld et al., 1994). Integrating measures of chemical availability with digestibility assays can yield better estimates of bioavailability, for example, reactive lysine in heat-treated feed ingredients (Carpenter, 1973; Batterham, 1992; Rutherfurd and Moughan, 1997; Pahm et al., 2009). Thus, there is a need to develop assays based on the analyses of reactive amino acids in both ileal digesta and feed. There is also increasing evidence that ileal digestibility values underestimate amino acid bioavailability of diets high in fermentable fiber or diets that induce high rates of endogenous gut losses or fermentative amino acid catabolism (Zhu et al., 2005; Libao-Mercado et al., 2006, 2009).

Apparent ileal digestibility estimates do not differentiate between dietary undigested and unabsorbed amino acids and endogenous amino acids at the terminal ileum. Endogenous protein and amino acids consist of protein from gastric, pancreatic, and biliary secretions, sloughed off mucosal cells, and endogenous ammonia and urea. Obtaining true digestibility requires the correction of digesta amino acids for endogenous losses. The endogenous amino acids losses are affected by various factors, including dietary levels of antinutritional factors (e.g., trypsin inhibitors, tannins), fat, fiber, and protein (Stein et al., 2007). The two main components of ileal endogenous amino acids include basal and specific ileal endogenous amino acid losses. The basal losses have also been referred to as diet-independent or nonspecific endogenous losses, and the specific endogenous losses as diet-dependent endogenous losses. The sum of basal and specific losses constitutes the total ileal endogenous losses. Correction of apparent ileal digestibility of amino acids for total ileal endogenous amino acid losses gives true ileal digestibility of amino acids, while correction for basal ileal endogenous amino acid losses gives standardized ileal digestibility of amino acids. The universal adoption of standardized ileal digestibility of amino acids and the methodology for its determination in feeds were proposed by Stein et al. (2007). In this publication, basal endogenous losses of amino acids are accounted for, and therefore both requirements and ingredient contents are expressed in terms of standardized ileal digestible amino acids.

Several studies (reviewed by Lewis and Bayley, 1995) have shown that crystalline amino acids are fully absorbed from the lumen of the small intestine. They are, therefore, usually assumed to be 100% bioavailable. However, there are situations in which amino acids can be fully absorbed but not fully bioavailable. Examples of these are heat damage of lysine resulting in derivatives (e.g., ε-N-deoxyketosyllysine, an Amadori product formed from a Maillard reaction) that are absorbed but cannot be utilized and infrequent feeding leading to rapid absorption of crystalline amino acids relative to amino acids from intact proteins. Additional aspects of bioavailability, specifically digestibility, are discussed in detail in Chapter 13.

DIETARY DISPROPORTIONS OF AMINO ACIDS

The ingestion of disproportionate amounts of amino acids may result in adverse effects such as amino acid deficiency, amino acid toxicity, amino acid antagonism, or amino acid imbalance (Harper et al., 1970; D'Mello, 2003). Amino acid deficiency is a condition in which the dietary supply of one or more of the essential amino acids is less than that required for efficient utilization of other amino acids and other nutrients. Protein supplements used in swine diets are unlikely to be devoid of an essential amino acid but may be deficient in one or more. The amino acid for which the dietary supply provides the lowest proportion of the theoretical requirement is referred to as the first-limiting amino acid, the amino acid for which the dietary supply provides the second lowest proportion of the requirement is the second limiting, and so on. There are few characteristic clinical signs of amino acid deficiencies in swine. The primary sign is usually a reduction in feed intake that may be accompanied by increased feed wastage and impaired growth.

Swine can tolerate high intakes of protein with few specific ill effects, except occasional mild diarrhea. However, feeding high levels of protein (e.g., in excess of 25% protein to growing-finishing pigs) is wasteful, contributes to environmental pollution, and usually results in reduced weight gain and feed efficiency. Reduced feed intake, impaired growth, abnormal behavior, and even death can result from excess intake of specific amino acids.

Amino acid toxicity refers to adverse effects (such as gross, pathological signs) resulting from ingestion of large amounts of a single amino acid that is not preventable by supplementation with either one or a small group of other amino acids. Excessive ingestion of methionine or cysteine has been studied extensively in experimental animals and these sulfur amino acids are well established as being among the most toxic of all amino acids that have been studied (Baker, 2006; Dilger and Baker, 2008). Threonine is the least toxic essential amino acid (Edmonds et al., 1987) and the nonessential amino acids are generally less deleterious, with the possible exception of serine. The toxic effects responsible for the pathological changes are probably due to the structural and metabolic features of individual amino acids.

Amino acids that are chemically or structurally related may compete with one another and cause inhibition of their use in protein synthesis. Amino acid antagonism is a specific interaction between structurally or chemically related amino acids whereby the introduction into the diet of an excess amount of one amino acid within the group (mutually antagonistic group) increases the requirement for the other amino acids, and supplementation with the first-limiting amino acid of the original diet does not correct the adverse effect on animal performance. Examples of these include antagonisms among the neutral and branched-chain amino acids (leucine, isoleucine, and valine), which are important in growing pigs (Langer and Fuller, 2000; Langer et al., 2000; Wiltafsky et al., 2010) and sows (Guan et al., 2004; Perez-Laspiur et al., 2009) and between lysine and arginine, which is generally of little practical significance in pigs (Lewis, 2001). Antagonisms among the branched-chain amino acids may result from increased catabolism of branched-chain amino acids, which also leads to catabolism of the branched-chain amino acids that is first-limiting. In general, the adverse effects are alleviated by addition of a chemically or structurally similar amino acid.

An amino acid imbalance occurs regardless of structure and may result when diets are supplemented with one or more amino acids other than the limiting amino acid. A reduction in feed intake is common in most of these situations. Amino acid imbalance is usually alleviated by supplementation with a small amount of one or more of the limiting amino acids. Amino acid antagonism or imbalance may result from competition for and impairment of intestinal amino acid absorption and transport; metabolic disturbance; and copious release of toxic substances such as ammonia and homocysteine. A reduction in feed intake is common in most of these situations in swine and recovery is rapid when the offending amino acid is removed from the diet. The effects of excess intakes of amino acids on physiological and metabolic responses have been reviewed by Harper et al. (1970), Benevenga and Steele (1984), and Garlick (2004).

RATIOS OF AMINO ACIDS TO LYSINE

Based on the observation that the amino acid composition of high-quality protein for growing animals resembled the amino acid composition of the tissue of the animals, the concept of expressing dietary amino acid requirements on an ideal amino acid profile was developed. The ideal profile later became known as "ideal protein." The assumption is that an ideal dietary profile (or ideal protein) contains the optimum balance of all amino acids required for maintenance and productive functions for a clearly defined physiological state. As in the tenth edition of this publication (NRC, 1998), the concept of an optimal dietary pattern among essential amino acids was applied to the major physiological processes that contribute to amino acid requirements. Therefore, the optimum dietary amino acid balance varies with physiological state and level of productivity of the animal. The present edition expands on the optimum ratio of amino acids to lysine employed in the tenth edition using other available information on amino acid composition of basal endogenous intestinal losses, integument (skin and hair) losses, and protein gain (in whole empty body for growing-finishing pigs, in conceptus and maternal tissues for gestating sows, and in milk and maternal tissues for lactating sows). The procedures for establishing these optimum ratios of amino acids are described later in this chapter.

EMPIRICAL ESTIMATES OF AMINO ACID REQUIREMENTS

Traditionally, nutrient requirements were based solely upon a summarization of empirical studies. There are, however, limitations in this approach as these studies are time-dependent based on rates of lean and fat deposition, feed intake, health status, and environmental conditions for specific experiments. Consequently, there is an increased emphasis on factorial estimation of amino acid requirements. For model development and testing, a comprehensive review of empirical studies is deemed necessary. Empirical determination of amino acid requirements demands careful attention to details of proper animal models, suitable environmental conditions, and adequate diets that allow meaningful extrapolation to practical settings. Despite extensive research, some aspects of amino acid requirements (such as additivity and impacts of environmental conditions) remain poorly defined even for lysine, methionine, tryptophan, and threonine, which are often deficient in practical diets. Much less is known about the requirements for the 5th to 8th limiting amino acids; as crystalline amino acids become more widely available, it will become critical to have good requirement estimates for all essential amino acids. Critical needs for studies designed to determine amino acid requirements include: (1) a basal diet that is deficient in the test amino acid using feed ingredients deficient in the amino acid (this may require supplementing the basal diet with other crystalline amino acids to ensure that the test amino acid is first-limiting); (2) the basal diet has to contain adequate levels of other nutrients except the test amino acid; (3) at least four graded levels of test amino acid (deficient to excess levels; two levels each above and below the estimated requirement); (4) adequate duration, which depends on the response criteria; and (5) an appropriate statistical model for objective description of response and determination of requirement. An extensive survey of published literature on amino acid requirements of pigs was carried out for this publication and is presented below.

To maintain consistency in estimating requirements among different amino acids and stages of growth, the "requirement" was determined using breakpoint methodology (Robbins et al., 2006). For growing pigs the requirement was based on average daily gain relative to levels of the dietary amino acid in question, whereas for gestation and lactation, additional parameters (as outlined below) were also taken into consideration. Furthermore, if the amino acid composition or the standardized ileal digestible amino acid concentrations of the diets were not provided, a common nutrient and ileal digestible amino acid database was used (NRC, 1998) to reduce variation when comparing studies. In the few exceptions where there was no composition or digestibility coefficient estimate for a specific ingredient, additional databases (AmiPig, 2000; AminoDat, 2006) were consulted.

Starting and Growing-Finishing Pigs

Several criteria were used in selecting studies, including, but not limited to, ingredient and/or nutrient composition of diets from which information on standardized ileal digestibility of amino acids and metabolizable energy could be calculated, adequate replication, a basal diet deficient in the amino acid of interest but containing adequate levels of other nutrients, multiple levels of the amino acid of interest ranging from deficiency to above the perceived requirement, and a significant production response such as average daily gain. From selected studies an estimated requirement was obtained and a standardized ileal digestible amino acid level estimated from the diet composition at the defined requirement. In addition, dietary metabolizable energy content, pig body weight (average, initial, and final), and the associated performance parameters (average daily gain and average daily feed intake) at the estimated requirement were also recorded. Lastly, grams of standardized ileal digestible amino acid requirement per kilogram BW gain were also calculated from the summarized data. The synopsis of this literature review is presented in Table 2-2.

Gestating Sows

For the gestating sow, studies were selected based on similar criteria as described for growing-finishing pigs, with the exception that a few studies were included despite that only three dietary amino acid inclusion levels were used. When available, the following parameters of performance measures were recorded: sow feed intake, sow BW at breeding (day 1) and end of gestation (day 113), number of pigs born (live + dead), pig weight at birth, and production response such as nitrogen retention, plasma amino acid response, or indicator amino acid oxidation. Similar to the growing-finishing pig review, the standardized ileal digestible amino acid requirements were calculated based on the dietary ingredient composition of each study and the standardized ileal digestibility amino acid content. Unlike the abundance of research in growing-finishing pigs, only four studies for lysine (Rippel et al., 1965a; Duée and Rérat, 1975; Woerman and Speer, 1976; Dourmad and Étienne, 2002), four for threonine (Rippel et al., 1965a; Leonard and Speer, 1983; Dourmad and

TABLE 2-2 Summary of Amino Acid Requirement Estimates in Growing-Finishing Pigs and Associated Performance Parameters[a]

	BW (kg)			Performance		Diet	SID	
Reference	Mean	Initial	Final	ADG	ADFI	ME	%	g/kg gain
Lysine								
Lewis et al. (1980)	10.0	5	15	397	710	3,300	1.100	19.67
Martinez and Knabe (1990)	10.6	6	15	325	631	3,400	1.060	20.58
Kendall et al. (2008)	15.0	11	19	526	688	3,421	1.350	17.66
Schneider et al. (2010)	15.2	9	21	588	783	3,667	1.350	17.98
Oresanya et al. (2007)	15.5	8	23	554	840	3,500	1.480	22.44
Schneider et al. (2010)	16.0	10	22	584	900	3,667	1.150	17.72
Williams et al. (1997)	17.0	7	27	677	977	3,452	1.218	17.58
Nam and Aherne (1994)	17.5	9	26	612	1,035	3,513	1.179	19.94
Kendall et al. (2008)	18.0	11	25	625	865	3,421	1.260	17.44
Yi et al. (2006)	18.5	12	25	586	889	3,420	1.280	19.42
Kendall et al. (2008)	19.0	11	27	646	958	3,421	1.300	19.28
Urynek and Buraczewska (2003)	21.9	13	31	634	1,190	3,346	1.148	21.55
O'Connell et al. (2005)	30.5	21	40	789	1,354	3,166	1.153	19.78
Bikker et al. (1994b)	32.5	20	45	768	1,272	3,671	0.827	13.69
Batterham et al. (1990)	32.5	20	45	680	1,288	3,511	0.840	15.91
Batterham et al. (1990)	32.5	20	45	625	1,299	3,511	0.713	14.82
Martinez and Knabe (1990)	34.8	21	49	786	1,994	3,264	0.820	20.80
Lawrence et al. (1994)	35.0	20	50	968	1,976	3,362	0.880	17.96
Krick et al. (1993)	39.5	20	59	921	2,198	3,350	0.942	22.47
Williams et al. (1984)	40.0	25	55	875	2,144	3,348	0.757	18.54
Warnants et al. (2003)	40.0	31	49	601	1,260	3,166	1.090	22.85
Warnants et al. (2003)	40.0	31	49	649	1,400	3,166	1.140	24.59
O'Connell et al. (2005)	51.0	40	62	833	1,922	3,166	0.994	22.94
O'Connell et al. (2005)	55.0	42	68	968	1,967	3,166	1.118	22.71
Hahn et al. (1995)	71.5	52	91	970	2,798	3,485	0.640	18.46
Hahn et al. (1995)	71.5	52	91	1,150	3,497	3,485	0.560	17.03
O'Connell et al. (2006)	75.5	60	91	980	2,427	3,166	0.950	23.54
Williams et al. (1984)	80.0	55	105	870	2,540	3,315	0.651	19.02
Ettle et al. (2003)	83.5	56	111	1,068	2,890	3,227	0.675	18.27
Cline et al. (2000)	85.0	54	116	850	2,730	3,370	0.748	24.02
Friesen et al. (1995)	88.0	72	104	890	2,890	3,462	0.710	23.06
O'Connell et al. (2006)	89.5	80	99	905	2,525	3,166	0.818	22.83
O'Connell et al. (2006)	91.5	81	102	880	2,451	3,166	0.871	24.26
Dourmad et al. (1996b)	95.5	80	111	902	2,832	3,075	0.600	18.84
Dourmad et al. (1996b)	95.5	80	111	896	2,822	3,075	0.602	18.96
Yen et al. (2005)	98.5	84	113	790	2,990	3,400	0.440	16.65
Hahn et al. (1995)	99.5	91	108	993	2,796	3,468	0.520	14.64
Hahn et al. (1995)	99.5	91	108	1,118	3,945	3,468	0.500	17.64
King et al. (2000)	100.0	80	120	934	2,479	3,327	0.580	15.39
King et al. (2000)	100.0	80	120	976	2,390	3,327	0.667	16.33
Loughmiller et al. (1998a)	102.0	91	113	800	3,000	3,303	0.469	17.59
Friesen et al. (1995)	120.0	104	136	830	3,150	3,462	0.650	24.67
Arginine								
Southern and Baker (1983)	12.0	9.0	15.0	508	806	3,582	0.480	7.62
Histidine								
Izquierdo et al. (1988)	14.8	10.0	19.5	453	594	3,200	0.252	3.31
Isoleucine								
Becker et al. (1963)	8.2	5.1	11.2	197	340	3,799	0.616	10.63
Kerr et al. (2004)	8.3	6.6	9.9	255	355	3,440	0.654	9.11
Kerr et al. (2004)	8.8	6.6	10.9	314	410	3,440	0.690	9.01
Oestemer et al. (1973)	11.6	5.8	17.4	385	648	3,143	0.514	8.64
Wiltafsky et al. (2009)	15.5	7.7	23.2	444	621	3,251	0.601	8.41
Wiltafsky et al. (2009)	17.1	8.0	26.2	433	616	3,251	0.501	7.12
Becker et al. (1957)	21.5	14.7	28.2	450	957	3,152	0.350	7.44

continued

TABLE 2-2 Continued

Reference	BW (kg) Mean	Initial	Final	Performance ADG	ADFI	Diet ME	SID %	g/kg gain
Becker et al. (1957)	21.5	14.2	28.7	484	848	3,335	0.513	8.98
Parr et al. (2003)	34.5	27.0	42.0	709	1,464	3,430	0.453	9.35
Taylor et al. (1985)	40.0	25.0	55.0	630	1,598	3,590	0.381	9.68
Becker et al. (1963)	53.0	44.6	61.3	595	1,780	3,533	0.291	8.71
Leucine								
Augspurger and Baker (2004)	13.4	9.2	17.5	480	797	3,490	1.050	17.44
Methionine								
Chung and Baker (1992b)	8.4	6	11	321	518	3,476	0.315	5.08
Owen et al. (1995)	8.9	5	13	372	413	3,478	0.363	4.03
Matthews et al. (2001)	10.2	6	14	367	546	3,354	0.420	6.25
Owen et al. (1995)	10.6	6	15	439	658	3,326	0.319	4.78
Chung and Baker (1992b)	18.1	11	25	645	1,174	3,476	0.275	5.01
Yi et al. (2006)	19.5	13	26	650	956	3,420	0.440	6.47
Schutte et al. (1991)	25.5	13	38	440	1,010	3,221	0.320	7.35
Schutte et al. (1991)	26.0	14	38	628	1,212	3,221	0.290	5.60
Leibholz (1984)	28.0	21	35	505	1,353	3,465	0.180	4.82
Lenis et al. (1990)	50.0	35	65	835	1,990	3,268	0.270	6.43
Lenis et al. (1990)	50.0	35	65	847	2,070	3,268	0.230	5.62
Leibholz (1984)	53.0	35	71	618	2,064	3,465	0.157	5.23
Chung et al. (1989)	66.4	53	80	946	2,680	3,512	0.175	4.96
Roth et al. (2000)	79.0	53	105	769	2,410	3,083	0.180	5.64
Roth et al. (2000)	80.5	54	107	837	2,440	3,083	0.220	6.41
Roth et al. (2000)	80.5	54	107	869	2,500	3,083	0.210	6.04
Loughmiller et al. (1998b)	82.5	54	111	890	3,050	3,203	0.230	7.88
Loughmiller et al. (1998b)	89.0	74	104	880	2,410	3,474	0.125	3.42
Knowles et al. (1998)	92.7	74	111	780	3,320	3,478	0.135	5.75
Methionine + Cysteine								
Matthews et al. (2001)	10.2	6	14	367	546	3,354	0.801	11.92
Yi et al. (2006)	19.5	13	26	650	956	3,420	0.770	11.32
Schutte et al. (1991)	25.5	13	38	440	1,010	3,221	0.520	11.94
Schutte et al. (1991)	26.0	14	38	628	1,212	3,221	0.540	10.42
Lenis et al. (1990)	50.0	35	65	835	1,990	3,268	0.460	10.96
Lenis et al. (1990)	50.0	35	65	847	2,070	3,268	0.430	10.51
Chung et al. (1989)	66.4	53	80	946	2,680	3,512	0.410	11.61
Roth et al. (2000)	79.0	53	105	769	2,410	3,083	0.366	11.47
Roth et al. (2000)	80.5	54	107	837	2,440	3,083	0.350	10.20
Roth et al. (2000)	80.5	54	107	869	2,500	3,083	0.413	11.88
Loughmiller et al. (1998b)	82.5	54	111	890	3,050	3,203	0.392	13.43
Loughmiller et al. (1998b)	89.0	74	104	880	2,410	3,474	0.335	9.17
Knowles et al. (1998)	92.7	74	111	780	3,320	3,478	0.250	10.64
Threonine								
Ragland and Adeola (1996)	15.1	9.8	20.3	405	1,158	3,456	0.398	11.38
Kovar et al. (1993)	15.2	10.9	19.4	442	975	3,388	0.455	10.03
Adeola et al. (1994)	15.4	9.9	20.9	416	998	3,936	0.454	10.90
Adeola et al. (1994)	15.4	9.9	20.9	492	1,068	3,936	0.507	11.01
Bergstrom et al. (1996)	17.1	11.4	22.7	497	1,117	3,314	0.475	10.67
Ferguson et al. (2000)	19.0	12.9	25.0	621	1,034	3,327	0.622	10.36
Conway et al. (1990)	33.5	17.0	50.0	486	1,208	3,180	0.514	12.77
Sève et al. (1993)	37.5	25.0	50.0	635	1,501	3,072	0.503	11.90
de Lange et al. (2001)	58.0	39.0	77.0	866	1,620	3,262	0.538	10.06
Cohen and Tanksley (1977)	74.0	58.9	89.1	756	2,961	3,064	0.298	11.67
Saldana et al. (1994)	75.7	58.0	93.3	897	3,020	3,245	0.299	10.06
Rademacher et al. (1997)	81.5	60.0	103.0	976	3,243	3,107	0.411	13.66
Johnston et al. (2000)	103.9	92.0	115.8	873	2,953	3,373	0.338	11.44
Tryptophan								
Guzik et al. (2002)	6.3	5.2	7.3	190	300	3,300	0.205	3.24

TABLE 2-2 Continued

	BW (kg)			Performance		Diet	SID	
Reference	Mean	Initial	Final	ADG	ADFI	ME	%	g/kg gain
Guzik et al. (2002)	8.3	6.3	10.2	322	511	3,300	0.182	2.88
Burgoon et al. (1992)	11.0	6.2	15.7	343	500	3,446	0.168	2.46
Cadogan et al. (1999)	11.4	6.1	16.6	498	526	3,442	0.257	2.71
Guzik et al. (2002)	13.0	10.3	15.7	440	765	3,300	0.180	3.13
Sato et al. (1987)	13.3	10.0	16.6	314	775	3,226	0.153	3.78
Eder et al. (2001)	13.4	7.5	19.3	344	600	3,107	0.154	2.69
Boomgaardt and Baker (1973)	15.1	10.4	19.7	396	896	3,182	0.111	2.52
Borg et al. (1987)	15.9	9.7	22.0	437	943	3,192	0.135	2.91
Russell et al. (1983)	26.4	18.4	34.3	620	1,500	3,285	0.153	3.71
Schutte et al. (1995)	30.0	20.0	40.0	734	1,393	3,212	0.188	3.57
Quant et al. (2012)	34.1	25.7	42.5	801	1,721	3,349	0.112	2.40
Burgoon et al. (1992)	36.2	21.9	50.5	815	1,723	3,600	0.127	2.68
Quant et al. (2012)	37.3	28.5	46.2	844	1,738	3,325	0.114	2.34
Eder et al. (2003)	37.5	25.0	50.0	774	1,640	3,344	0.131	2.77
Eder et al. (2003)	65.0	50.0	80.0	876	2,150	3,331	0.147	3.61
Burgoon et al. (1992)	76.4	55.4	97.3	998	3,090	3,456	0.075	2.34
Guzik et al. (2005)	89.9	74.6	105.1	900	3,400	3,297	0.094	3.54
Eder et al. (2003)	97.5	80.0	115.0	746	2,752	3,243	0.093	3.43
Valine								
Mavromichalis et al. (2001)	7.6	5.8	9.4	258	292	3,445	0.863	9.77
Wiltafsky et al. (2009)	14.8	7.9	21.6	409	573	3,275	0.659	9.24
Mavromichalis et al. (2001)	15.1	10.9	19.2	519	847	3,487	0.674	11.00
Barea et al. (2009)	17.8	12.8	22.7	473	843	3,233	0.659	11.75
Wiltafsky et al. (2009)	18.8	14.1	23.4	333	516	3,275	0.614	9.51
Gaines et al. (2011)	20.3	13.5	27.0	641	1,100	3,350	0.683	11.72
Gaines et al. (2011)	27.0	21.4	32.6	805	1,378	3,350	0.724	12.38

[a]For each citation, dietary metabolizable energy (ME) and percent standardized ileal digestible (SID) were calculated from the diet composition at the estimated requirement as described in the text.

Étienne, 2002; Levesque et al., 2011), three for tryptophan (Rippel et al., 1965c; Easter and Baker, 1977; Meisinger and Speer, 1979), one for isoleucine (Rippel et al., 1965a), two for methionine + cysteine (Rippel et al., 1965a; Holden et al., 1971), and one for valine (Rippel et al., 1965c) were selected in the review. The synopsis of this literature review is presented in Table 2-3.

Lactating Sows

Studies were selected based on similar criteria as described previously, but additional parameters were required and recorded: length of lactation, number of pigs weaned, initial and final sow BW or BW change, and litter weight gain (or milk production). Only 10 papers met the selection criteria for lysine (Lewis and Speer, 1973; O'Grady and Hanrahan, 1975; Chen et al., 1978; Johnston et al., 1993; King et al., 1993b; Knabe et al., 1996; Tritton et al., 1996; Sauber et al., 1998; Touchette et al., 1998; Yang et al., 2000), three for threonine (Lewis and Speer, 1975; Westermeier et al., 1998; Cooper et al., 2001), two for methionine plus cysteine (Ganguli et al., 1971; Schneider et al., 1992b), two for tryptophan (Lewis and Speer, 1974; Paulicks et al., 2006), and two for valine (Rousselow and Speer, 1980; Paulicks et al., 2003). The synopsis of this literature review is presented in Table 2-4.

DETERMINANTS OF AMINO ACID REQUIREMENTS—A MODELING APPROACH

Amino acids required for biological processes in pigs are released from protein digestion, absorbed from the gastrointestinal tract, and metabolized to support both metabolism and protein retention (for growth and reproduction, including milk protein production). Requirements for amino acids therefore represent the sum of those for body maintenance functions and for protein retention. Amino acids for milk protein production may be derived from dietary intake or mobilized body protein. During lactation, maternal body protein losses should be minimized to improve subsequent reproductive performance, especially in parity-1 sows (e.g., Boyd et al., 2000). Provided that the sows' dietary amino acid intake is sufficient, maternal body protein mobilization during lactation is driven by energy intake. Therefore, the

TABLE 2-3 Summary of Amino Acid Requirement Estimates in Gestating Sows and Associated Performance Parameters

Authors	Parity	BW (day 1)	BW (day 113)	Total Litter Size	Pig BW at Birth (kg)	ADFI (kg)	Diet ME (kcal/kg)[a]	Diet SID (%)[a]	Diet SID (g/day)	N Retention (g/day)
Lysine										
Rippel et al. (1965a)[b]	1	—	—	10.88	1.224	1.82	3,340	0.358	6.51	13.95
Duée and Rérat (1975)[c]	1	109.4	156.7	8.00	1.250	2.00	3,226	0.542	10.85	12.80
Woerman and Speer (1976)[d]	1	130.3	142.4	9.80	1.306	1.82	3,263	0.547	9.95	9.40
Dourmad and Étienne (2002)[e]	> 1	228.0	265.0	12.80	1.450	2.75	3,278	0.430	11.84	14.70
Threonine										
Rippel et al. (1965a)[b]	1	—	—	8.90	1.476	1.82	3,340	0.389	7.07	16.68
Leonard and Speer (1983)[f]	2,3	131.0	184.6	9.45	1.407	1.82	3,360	0.299	5.44	7.10
Dourmad and Étienne (2002)[e]	—	219.0	259.0	12.10	1.540	2.75	3,078	0.271	7.46	13.20
Levesque et al. (2011)[g]	—	191.5	230.4	—	—	—	—	—	—	—
Phe AA oxidation	2 to 3	191.5	236.9	13.30	1.526	2.40	3,442	0.247	8.5	ND
Plasma Thr	2 to 3	191.5	236.9	13.30	1.526	2.40	3,442	0.218	7.5	ND
Tryptophan										
Rippel et al. (1965c)[b]	1	—	—	9.00	1.400	1.82	3,340	0.083	1.505	16.51
Easter and Baker (1977)[h]	1	—	—	—	—	2.00	2,960	0.070	1.400	9.80
Meisinger and Speer (1979)[i]	1	—	—	8.50	1.294	2.00	3,355	0.086	1.729	5.00
Isoleucine										
Rippel et al. (1965a)[b]	1	—	—	9.57	1.237	1.82	3,340	0.317	5.769	16.79
Methionine + Cysteine										
Rippel et al. (1965a)[b]	1	—	—	8.56	1.360	1.82	3,340	0.200	3.642	17.31
Holden et al. (1971)[j]	1	—	—	7.60	1.220	1.82	3,466	0.217	3.958	9.38
Valine										
Rippel et al. (1965c)[b]	1	—	—	9.75	1.313	1.82	3,340	0.517	9.416	16.88

[a]For each citation, dietary metabolizable energy (ME) and percent standardized ileal digestible (SID) were calculated from the diet composition at the estimated requirement as described in the text.
[b]N balance conducted between day 100 and 110.
[c]N balance initiated on day 80.
[d]Mean of reported N retention values obtained from N balance initiated on days 0, 30, 60, and 95 of gestation.
[e]N balance conducted over 4 periods between day 20 and 104; authors only reported mean value.
[f]N balance initiated on day 45 and day 90; authors only reported mean value.
[g]Mean of reported values estimated between days 30 and 54 and between days 87 and 111.
[h]N balance conducted between days 80 and 107; authors only reported mean value.
[i]N balance conducted from days 45 to 70 and from days 90 to 115; authors only reported mean value.
[j]Mean of reported N retention values obtained from N balance initiated on days 0, 30, 68, and 106 of gestation.
ND = not determined.

contribution of maternal body protein mobilization to dietary amino acid requirements of lactating sows is estimated from energy partitioning. This is discussed further in the section titled "Protein content of maternal body weight changes" later in this chapter. Aspects relating to the amino acid requirements of growing-finishing pigs and gestating and lactating sows for maintenance are described together based on common themes of requirements to cover endogenous intestinal losses and skin and hair losses.

Maintenance

Moughan (1999) described the main determinants of amino acid and nitrogen requirements for maintenance as basal endogenous intestinal amino acid losses, which can be related to feed intake; skin and hair amino acid losses, which can be a function of $BW^{0.75}$; and minimum amino acid catabolism, which is associated with basal turnover of body proteins and the irreversible synthesis of essential nitrogenous compounds and contributes to (minimum) urinary urea excretion. Insufficient quantitative information was deemed available to generate reasonable estimates of minimum catabolism of individual amino acids. Therefore, the postabsorptive inefficiency (discussed below) of using standardized ileal amino acids intake for covering losses of intestinal, skin, and hair amino acids was assumed to account for amino acid losses associated with basal body protein turnover. Thus, amino acid needs for maintaining a pig at zero nitrogen retention when given adequate energy and nutrients are directed to the aforementioned processes.

TABLE 2-4 Summary of Amino Acid Requirement Estimates in Lactating Sows and Associated Performance Parameters[a]

Author	Parity	Lactation (days)	Pigs Weaned	Sow BW Change (kg/day)	Mean BW (kg)	ADFI (kg)	Diet ME (kcal/kg)	Diet SID (%)	SID Intake (g/day)	Litter Gain (g/day)
Lysine										
Chen et al. (1978)	1 to 2	21	9.5	–0.410	142	5.01	2,888	0.535	26.80	1,429
Johnston et al. (1993)	1 to 9	24	9.9	–0.086	199	6.27	3,270	0.687	43.07	2,120
King et al. (1993b)	1	29	9.0	–0.821	137	3.81	3,456	0.910	34.67	1,971
Knabe et al. (1996)	1	21	9.7	–0.152	185	5.64	3,378	0.590	33.28	1,668
Lewis and Speer (1973)	2 to 6	21	9.0	–0.762	192	5.45	3,224	0.490	26.71	1,665
O'Grady and Hanrahan (1975)	1 to 4	21	8.6	–0.319	161	5.45	2,880	0.470	25.61	1,348
Sauber et al. (1998)[b]	1	28	14	–1.224	144	4.74	3,224	0.66	31.28	2,286
Touchette et al. (1998)	1	17	10.0	–0.539	178	3.96	3,400	0.986	39.05	2,015
Tritton et al. (1996)	1	23	9.9	–1.139	162	4.45	3,174	0.655	29.15	2,000
Yang et al. (2000)	1 to 3	18	9.9	0.122	186	6.10	3,309	0.726	44.28	2,277
Threonine										
Cooper et al. (2001)	1 to 3	20	10.9	0.235	—	7.15	3,173	0.491	35.09	2,487
Lewis and Speer (1975)	3 to 7	21	9.0	–0.400	—	5.45	3,269	0.384	20.95	1,581
Westermeier et al. (1998)	1	21	9.3	–0.050	—	4.37	3,278	0.487	21.27	1,804
Methionine + Cysteine										
Ganguli et al. (1971)	1 to 5	21	8.0	–0.819	—	5.00	3,442	0.294	14.71	1,400
Schneider et al. (1992b)	2 to 8	21	9.5	–0.520	—	4.53	3,096	0.646	29.25	1,891
Tryptophan										
Lewis and Speer (1974)	3 to 6	21	9.0	–0.562	—	5.45	3,304	0.082	4.49	1,360
Paulicks et al. (2006)	> 1[c]	28	10.3	–0.685	—	4.66	3,158	0.148	6.88	1,896
Valine										
Paulicks et al. (2003)	> 1	21	11.0	–0.787	—	4.45	3,206	0.570	25.36	1.802
Rousselow and Speer (1980)	3 to 7	21	9.0	–0.238	—	5.50	3,466	0.531	29.20	1,022

[a]Lysine data used for estimation of utilization efficiency while data for the other amino acids (threonine and valine) used for model testing. For each citation, dietary metabolizable energy (ME) and percent standardized ileal digestible (SID) were calculated from the diet composition at the estimated requirement as described in the text.

[b]Values represent an average of the low and high lean gain potential used as part of the data set for estimation of lysine utilization efficiency.

[c]Indicates that multiparous sows were used but that the parity distribution is not reported in the study.

Basal amounts of amino acids of endogenous origin (from intestinal proteins) secreted into the intestinal tract and not recovered (reabsorbed) by the pig are related to dry matter intake. Based on the assumption that the contribution of the large intestine to the basal total intestinal endogenous amino acid losses (e.g., basal endogenous losses from the entire gastrointestinal tract) is approximately 10% of basal ileal endogenous losses (Moughan, 1999), basal total intestinal endogenous amino acid losses are taken as 110% of basal ileal endogenous losses. A weighted average of endogenous ileal amino acid losses in growing-finishing pigs fitted with ileal cannulas from 57 studies reported in the literature was used to generate a mean amino acid composition (g amino acid/kg dry matter intake) and profile (relative to lysine) of intestinal losses presented in Table 2-5. The weighted average endogenous ileal lysine loss per kilogram dry matter intake was 0.417 g from the 57 studies. In contrast, there are limited data on the profile of intestinal amino acid losses for gestating and lactating sows. Consequently, the amino acid profile shown in Table 2-5 was used for gestating and lactating sows, but lysine losses of 0.522 and 0.292 g/kg dry matter intake were used for gestating and lactating sows, respectively (Stein et al., 1999).

Amino acid losses via skin and hair are also a component of maintenance. The amino acids in skin and hair losses, as a function of $BW^{0.75}$, as well as the ratio among amino acids (expressed relative to lysine) used in generating maintenance estimates, were derived from van Milgen et al. (2008) and are presented in Table 2-5.

Basal intestinal endogenous losses of amino acids do not include effects that antinutritional factors and fiber may have on such losses. Daily basal endogenous losses of amino acids via the gastrointestinal tract are presented in Table 2-6. For example, for a growing pig consuming 2 kg dry matter daily, these values were calculated from the product of dry matter intake and 110% of basal ileal endogenous amino acid losses per kg dry matter intake (e.g., 0.417 × 1.1 for lysine, Table 2-5; 10% adjustment is to reflect the contribution from the hindgut to intestinal losses). Daily skin and hair amino acid losses listed in Table 2-6 were generated from

TABLE 2-5 Amino Acid Profile and Composition of Protein Losses via the Intestine, and Skin and Hair Losses

	Intestinal Losses				Skin and Hair Losses	
		g/kg DMI				
Amino Acid	g/100 g Lys	Growing-Finishing	Gestation	Lactation	g/100 g Lys	mg/kg $BW^{0.75}$
Arginine	116.4	0.485	0.608	0.340	0	0
Histidine	48.7	0.203	0.254	0.142	27.9	1.26
Isoleucine	91.9	0.383	0.480	0.268	55.8	2.51
Leucine	125.9	0.525	0.657	0.368	116.3	5.23
Lysine	100	0.417	0.522	0.292	100	4.5
Methionine	27.3	0.114	0.143	0.080	23.3	1.05
Methionine + cysteine	78.1	0.326	0.408	0.228	127.9	5.76
Phenylalanine	82.2	0.343	0.429	0.240	67.4	3.03
Phenylalanine + tyrosine	150.4	0.627	0.785	0.439	109.3	4.92
Threonine	145.1	0.605	0.757	0.424	74.4	3.35
Tryptophan	31.8	0.133	0.166	0.093	20.9	0.94
Valine	129.8	0.541	0.678	0.379	83.7	3.77
N × 6.25	3,370.4	14.05	17.59	9.84	2,325.6	104.7

the product of amino acid losses in Table 2-5 and $BW^{0.75}$. Amino acid requirements for maintenance represent the sum of the physical losses divided by the efficiency of amino acid utilization for body maintenance functions listed in Table 2-12; the approach used to estimate the efficiencies of amino acid utilization is described in detail later in this chapter. Amino acid requirements for maintenance are presented in Table 2-7 for a 50-kg growing pig, a 200-kg gestating sow, and a 200-kg lactating sow on the basis of g/day, mg/kg $BW^{0.75}$ per day, or amino acid profile relative to lysine. The profile (ratio) of amino acid requirements for maintenance in different weights and classes of pigs used in this publication were derived as described above. This represents a departure from the fixed 36 mg lysine/kg $BW^{0.75}$ used in the tenth edition (NRC, 1998) and results in maintenance requirements for lysine of 71, 35, and 46 mg lysine/kg $BW^{0.75}$ for a 50-kg growing pig, a 200-kg gestating sow, and a 200-kg lactating sow, respectively (Table 2-7). By specifically identifying the maintenance amino acid requirements associated with skin and hair losses and endogenous intestinal losses, the substantial contribution of amino acid metabolism in visceral organs, represented as feed intake effects on basal endogenous intestinal amino acid losses, is represented more explicitly.

Protein Deposition and Retention and Its Amino Acid Composition

Growing Pigs

In growing pigs, the dietary supply of amino acids above the needs for maintenance can be used for body protein deposition up to the pig's maximal body protein deposition

TABLE 2-6 Daily Losses of Amino Acids via the Intestine and Skin and Hair During Growth, Gestation, and Lactation

	50-kg Pig (2 kg DMI/day)		200-kg Gestating Sow (2 kg DMI/day)		200-kg Lactating Sow (5 kg DMI/day)	
Amino Acid	Intestinal (g/day)	Skin and Hair (g/day)	Intestinal (g/day)	Skin and Hair (g/day)	Intestinal (g/day)	Skin and Hair (g/day)
Arginine	0.726	0.000	0.909	0.000	2.045	0.000
Histidine	0.447	0.024	0.574	0.069	0.967	0.083
Isoleucine	1.110	0.062	1.406	0.178	1.890	0.171
Leucine	1.538	0.131	1.607	0.309	2.497	0.344
Lysine	1.223	0.113	1.531	0.319	2.141	0.319
Methionine	0.343	0.027	0.414	0.074	0.480	0.061
Methionine + cysteine	1.189	0.179	1.459	0.498	1.553	0.379
Phenylalanine	1.123	0.085	1.137	0.194	1.690	0.207
Phenylalanine + tyrosine	1.850	0.124	2.101	0.318	2.982	0.323
Threonine	1.748	0.083	2.140	0.229	2.805	0.214
Tryptophan	0.478	0.029	0.512	0.070	0.676	0.066
Valine	1.489	0.089	1.773	0.238	3.193	0.307
N × 6.25	36.376	2.315	45.536	6.548	63.681	6.548

TABLE 2-7 Standardized Ileal Digestible Amino Acid Requirements and the Optimum Ratio for Maintenance

	50-kg Pig (2 kg DMI/day)			200-kg Gestating Sow (2 kg DMI/day)			200-kg Lactating Sow (5 kg DMI/day)		
Amino Acid	g/day	mg/kg $BW^{0.75}$	Ratio to Lys	g/day	mg/kg $BW^{0.75}$	Ratio to Lys	g/day	mg/kg $BW^{0.75}$	Ratio to Lys
Arginine	0.73	38.62	54.4	0.91	17.09	49.1	2.04	38.45	83.1
Histidine	0.47	25.00	35.2	0.64	12.09	34.8	1.05	19.74	42.7
Isoleucine	1.17	62.32	87.7	1.58	29.78	85.6	2.06	38.76	83.8
Leucine	1.67	88.78	124.9	1.92	36.03	103.6	2.84	53.41	115.4
Lysine	1.34	71.05	100.0	1.85	34.79	100.0	2.46	46.26	100.0
Methionine	0.37	19.68	27.7	0.49	9.17	26.4	0.54	10.16	22.0
Methionine + cysteine	1.37	72.77	102.4	1.96	36.80	105.8	1.93	36.33	78.5
Phenylalanine	1.21	64.27	90.5	1.33	25.03	72.0	1.90	35.66	77.1
Phenylalanine + tyrosine	1.97	104.96	147.7	2.42	45.49	130.8	3.31	62.14	134.3
Threonine	1.83	97.33	137.0	2.37	44.53	128.0	3.02	56.78	122.7
Tryptophan	0.51	26.98	38.0	0.58	10.94	31.4	0.74	13.97	30.2
Valine	1.58	83.89	118.1	2.01	37.82	108.7	3.50	65.81	142.3
N × 6.25	38.69	2,057.73	2,896.0	52.08	979.33	2,814.9	70.23	1,320.51	2,854.3

capacity. Body protein deposition and thus protein gain during growth represent the difference between protein synthesis and degradation. Further information about whole-body protein deposition as determined by BW, gender, feeding ractopamine, or immunizations against gonadotropin-releasing hormone is provided in Chapter 8.

Data on amino acid concentration in whole-body protein and amino acid composition of protein gain were obtained from the studies reported by Batterham et al. (1990), Kyriazakis and Emmans (1993), Bikker et al. (1994a), and Mahan and Shields (1998). Linear regression of amino acid in whole-body protein on whole-body protein content for BW between 20 and 45 kg for pigs fed three diets that were not limiting in lysine in the study reported by Batterham et al. (1990) were used to generate amino acid composition of protein gain. The regression coefficients reported by Kyriazakis and Emmans (1993) for pigs from 12 to 32 kg BW were used to derive whole-body protein and amino acids in whole-body protein, and these data were subsequently used to generate amino acid composition of protein gain by regression analyses. The amino acid composition of protein gain for pigs fed at three times maintenance from 20 and 45 kg BW was used as reported by Bikker et al. (1994a). The publication of Mahan and Shields (1998) has a robust data set of nine slaughter weights between 8 and 146 kg live weight, and linear regression of amino acid in whole-body protein on whole-body protein representing seven slaughter points for BW between 21 and 127 kg were used to generate amino acid composition of protein gain for growing-finishing pigs. The average of these four data sets was used as the lysine concentration of body protein gain (7.1 g lysine/100 g body protein gain), amino acid composition of body protein gain, and amino acid ratios relative to lysine. The ratio of amino acid in body protein gain of growing-finishing pigs used in this publication is presented in Table 2-8.

The amino acid profile for ractopamine-induced body protein deposition was adjusted based on the notion that feeding ractopamine at 10 mg/kg of the diet increases whole-body protein deposition, more so for muscle protein than nonmuscle protein (Schinckel et al., 2003; Webster et al., 2007; Table 2-8). This adjustment was based on the amino acid composition of muscle protein (Lloyd et al., 1978) and nonmuscle protein (e.g., whole-body protein minus muscle protein) and the assumed contribution of muscle protein to whole-body protein deposition of 54% in non-ractopamine-fed pigs and 81% in ractopamine-induced body protein deposition.

TABLE 2-8 Lysine Content and Amino Acid Profile of Whole-Body Protein Gain in Growing-Finishing Pigs and Ractopamine-Induced Body Protein Gain

	Whole Protein Gain	Ractopamine-Induced Body Protein Gain
	Lysine, g/100 g Whole-Body Protein Gain	
	7.10	8.24
Amino Acid	g Amino Acid/100 g Lysine	
Arginine	90.2	79.4
Histidine	45.2	37.5
Isoleucine	50.8	56.6
Leucine	100.0	93.7
Lysine	100.0	100.0
Methionine	27.9	30.2
Methionine + cysteine	41.8	44.1
Phenylalanine	52.2	49.5
Phenylalanine + tyrosine	89.9	89.7
Threonine	53.1	54.4
Tryptophan	12.8	14.3
Valine	66.2	64.2

Gestating Sows

In NRC (1998), amino acid requirements for gestation were based on maternal and fetal gain, and the amino acid composition of tissue accretion during gestation was based on that of the growing-finishing pig. Here, protein retention and amino acid profiles of six pools are considered explicitly: fetal litter, mammary tissue, placenta including associated chorioallantoic fluid, uterus, as well as energy intake and time-dependent maternal body protein deposition. The CP mass (i.e., grams of CP per pool) for four pools (i.e., fetal litter, mammary tissue, placenta including associated chorioallantoic fluid, and uterus) at different days of gestation was calculated from individual pool weights and CP concentrations reported in the literature. Citations, sampling days, and the respective pools obtained are presented in Table 2-9. Protein mass in the time-dependent and energy intake-dependent maternal body protein pools were also estimated as described below.

Protein Pools

Fetal litter CP concentration was calculated based on data from Noblet et al. (1985), Wu et al. (1999), Mathews (2004), Canario et al. (2007), Pastorelli et al. (2009), and Charneca et al. (2010). Fetal CP content in relation to day 45, 60, 72.5, 90, 102, 110, and 113 of gestation is shown in Figure 2-1A. Mammary CP concentration was calculated based on data from Kensinger et al. (1986) and Ji et al. (2006), with mammary tissue CP content on day 0 assigned a value of 0 be-

TABLE 2-9 Summary of Studies Selected for Estimation of Nitrogen Content of the Gestation Pools and Their Corresponding Sampling Days

	Fetal Tissue		Mammary Tissue		Placental Tissue		Uterine Fluid		Uterine Tissue	
Author	Weight	CP	Weight	CP	Weight	CP	Volume	CP	Weight	CP
Biensen et al. (1998)	70-75, 90, 110				70-75, 110		70-75, 90, 110			
Freking et al. (2007)	45, 65, 80-85, 105				45, 65, 80-85, 105					
Ji et al. (2005)	45, 60, 70-75, 90, 102, 112-114						45, 60, 70-75, 90, 102, 112-114			
Ji et al. (2006)			45, 60, 70-75, 90, 102, 110-114	45, 60, 70-75, 90, 102, 110-114						
Kensinger et al. (1986)			110							
Knight et al. (1977)	45, 60, 70-75, 90, 102				45, 60, 70-75, 90, 102		45, 60, 70-75, 90, 102	45, 60, 70-75, 90, 102	45, 60, 70-75, 90, 102	
McPherson et al. (2004)	45, 60, 70-75, 90, 102, 112-114					45, 60, 70-75, 90, 102, 112-114				
Noblet et al. (1985)	50, 70-75, 102	50, 70-75, 102			70-75, 102	50, 70-75, 102	50, 70-75, 102	50, 70-75, 102	50, 70-75, 102	50, 70-75, 102
Pike and Boaz (1972)					70-75					
Wu et al. (1999)	45, 60, 90, 110, 112-114	45, 60, 90, 110, 112-114								
Wu et al. (2005)	45, 60, 90, 110				45, 60, 90, 110		45, 60, 90, 110			
Current study				80, 100, 110						

cause of the near absence of mammary parenchymal tissue in nongravid sows. Mammary CP content in relation to day 45, 60, 72.5, 90, 102, 110, and 113 of gestation is shown in Figure 2-1B. Placental CP concentration was calculated based on data from Noblet et al. (1985) and McPherson et al. (2004). Placental CP content in relation to day 45, 50, 60, 72.5, 90, 102, 110, and 113 of gestation is shown in Figure 2-1C. Uterine CP concentration was calculated based on data from Knight et al. (1977) and Noblet et al. (1985). Uterine CP content in relation to day 0, 50, 72.5, and 102 of gestation is shown in Figure 2-1D.

Protein retention in the time-dependent and energy intake-dependent maternal body protein pools was estimated from whole-body nitrogen retention at different stages of gestation according to Dourmad et al. (1998) and as outlined by Dourmad et al. (2008) and in Chapter 8. In short, it was assumed that the relationship between energy intake above maintenance energy requirements and energy intake-dependent maternal body protein deposition was linear and constant across stages of gestation. Whole-body nitrogen retention that could not be associated with energy intake or reproductive tissues was then attributed to time-dependent maternal body protein deposition. Minor adjustments to the pattern of time-dependent maternal body protein deposition were made, based on the summary of studies presented in Table 2-10. For this summary, nitrogen retention data were allocated to four gestation periods (i.e., day 10-40, 40-65, 65-90, and 90-114), averaged, and expressed relative to day 65-90. Because the N retention data from Dourmad et al. (1998) appeared elevated relative to those reported in studies listed in Table 2-10, the relative values of 0.84, 0.75, 1.00, and 1.36 were used as adjustment factors, yielding the pattern of time-dependent maternal body protein deposition as presented in Figure 2-2.

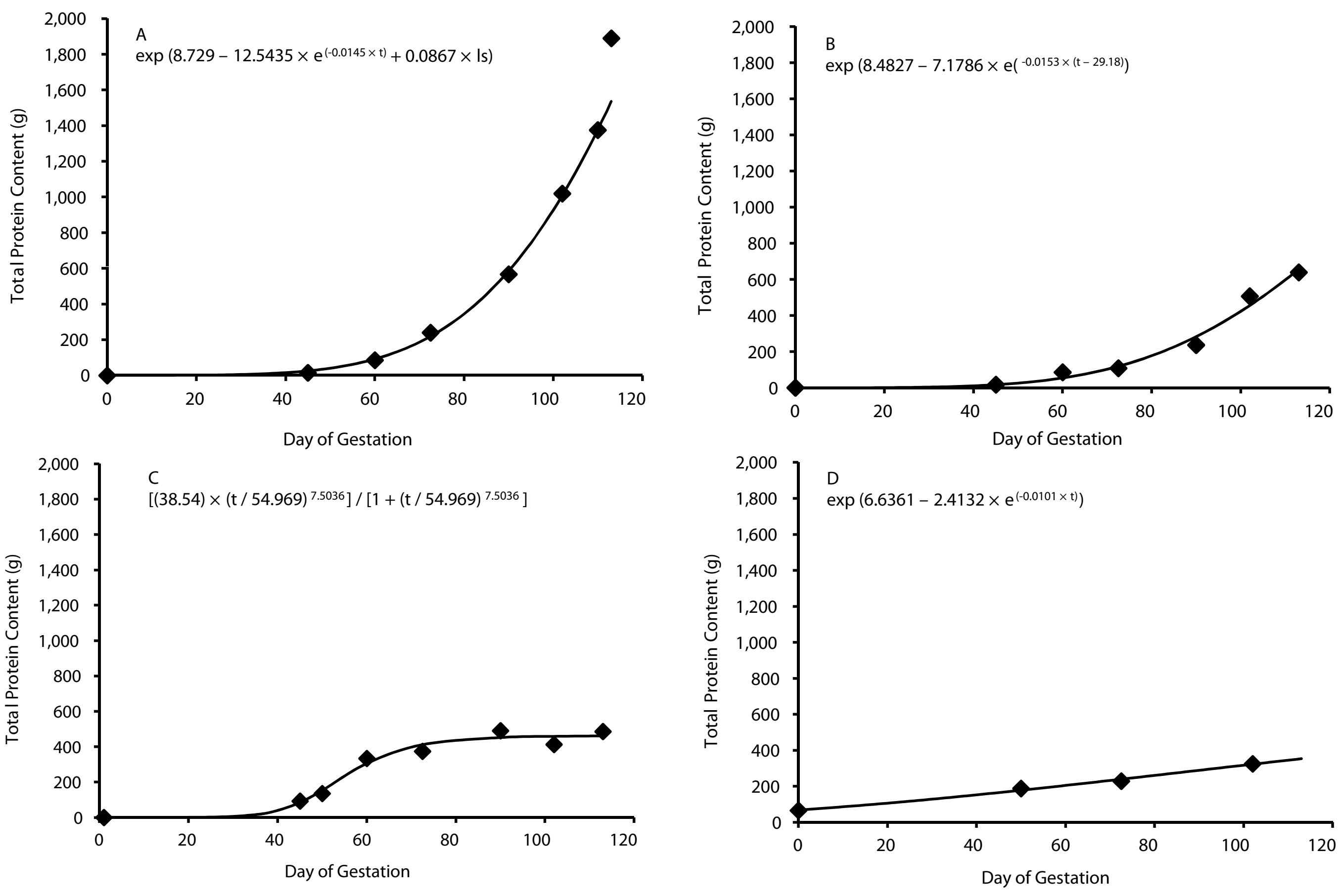

FIGURE 2-1 Relationship between total protein content (grams) in the fetal litter (n = 12) (panel A), udder (panel B), placenta and chorioallantoic fluids (panel C), and empty uterus (panel D) and day in gestation. The symbol (♦) represents the experimentally derived values as reported in Table 2-9 and the lines represent the predicted values based on the equations illustrated within each panel and as described in Chapter 8 (equation numbers 8-55, 8-59, 8-56, and 8-58, for fetal litter, udder, placenta and chorioallantoic fluids, and empty uterus, respectively), where "ls" represents litter size (n = 12) and t represents time (i.e., day in gestation).

TABLE 2-10 Summary of Nitrogen Retention (g/day) in Relation to Day of Gestation and the Associated Litter Performance

Author	Parity	Metabolizable Energy (kcal/day)	N Intake (g/day)	Litter Size at Birth	Pig Weight at Birth (kg)	Gestation Days 10-40	40-65	65-90	90-114
Rippel et al. (1965b)	1	6,078	34.94	10.4	1.365	—	—	13.67	16.88
Woerman and Speer (1976)	1	5,939	25.50	10.2	1.245	7.90	6.80	8.50	—
Willis and Maxwell (1984)	1	6,585	40.80	—	—	13.90	14.60	20.50	—
King and Brown (1993)[a]	1	9,499	23.31	—	—	10.00	12.10	16.50	—
Everts and Dekker (1994)	1	7,775	42.50	—	—	13.40	—	17.80	—
Dourmad et al. (1996a)[b]	> 1[c]	8,160	54.31	—	—	10.75	9.20	12.05	17.10
Clowes et al. (2003)[d]	1	7,120	52.73	9.3	1.450	17.70	—	14.80	21.20
Average based on relative contribution to day 65-90						0.84	0.75	1.00	1.36

[a]Mean of N intake of 22.72, 21.28, and 25.92 for gestation days 10-40, 40-65, and 65-90, respectively.
[b]Mean of N intake and N retention values for experiments 1 and 2.
[c]Indicates that multiparous sows were used but that the parity distribution is not reported in the study.
[d]N intake and retention values are those reported for the control group. Nitrogen intake value is the mean of 52.1, 51.8, and 54.3 for gestation days 10-40, 65-90, and 90-114, respectively. Litter size at birth not reported; value is litter size at weaning.

Amino Acid Composition of Gestational Protein Pools

The amino acid composition of whole maternal body protein was taken from Everts and Dekker (1995), which was determined on first-parity sows at day 108 of gestation and excluded the uterus, fetuses, and hair, but included the udder. The amino acid composition of fetal protein gain was based on the study by Wu et al. (1999). Mass of each amino acid per fetus was regressed against the fetal body protein mass on days 40, 60, 90, 108, and 114 of gestation. The product of 100 and the slope of the linear regression, with a forced intercept of 0, was taken as the amino acid profile, expressed as grams of amino acid per 100 g CP.

There were no published data on amino acid profiles in mammary tissue across stage of gestation in sows. Mammary tissue samples from gilts on day 80, 100, and 110 of gestation were obtained from Walter Hurley at the University of Illinois and these samples were analyzed for amino acid concentrations by Evonik-Degussa according to Llames and Fontaine (1994). Individual mammary gland dry weights of 74, 81, 101.1, and 118.4 g were obtained from Ji et al. (2006) for days 70, 90, 100, and 110 of gestation, respectively. Mammary gland weight between day 70 and 90 was averaged to represent day 80 gland weight of 77 g. The CP content of mammary tissue on day 80, 100, and 110 was determined to be 23.44, 35.23, and 43.98%, respectively, and was used to estimate the CP mass per gland (i.e., 18.05, 35.61, and 52.07 g). Thus the amino acid mass per gland was calculated based on the amino acid composition of the mammary protein and the CP content per gland. Mass of each amino acid (grams

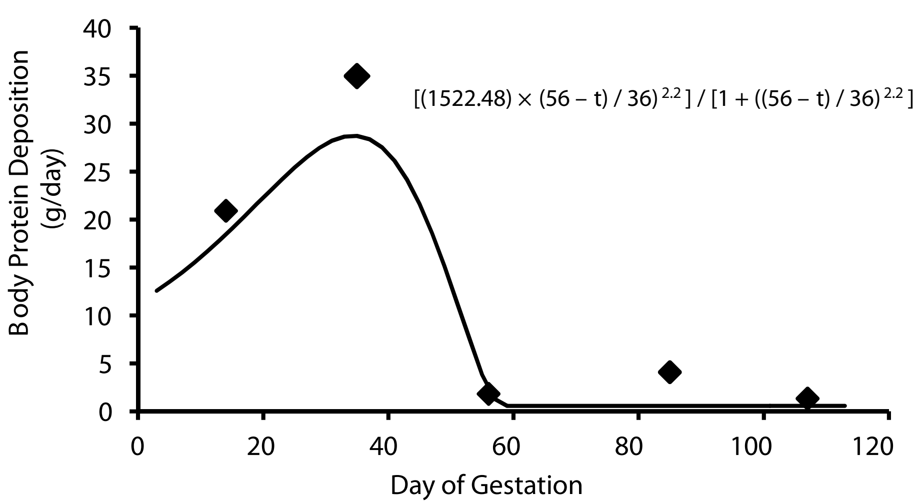

FIGURE 2-2 Relationship between time-dependent maternal body protein deposition (g/day) and day in gestation. The symbols (♦) represent the values estimated from Dourmad et al. (1998); Table 2-10; the line represents the predicted values based on the equation presented in the figure and reflects all values presented in Table 2-10.

of amino acid per mammary gland) was regressed against the mammary protein mass per gland on days 80, 100, and 110 of gestation to generate amino acid composition of mammary gland protein gain. Because individual mammary protein mass on day 80 was 18.05, whereas on day 45, it was estimated to be 1.5 g (Ji et al., 2006), a mammary protein mass of 0 was used for day 0 of gestation. The amino acid composition of the mammary protein gain across the entire gestation was based on the slope of the regression line, as carried out for amino acid composition of the fetal protein gain.

There were no published data on amino acid concentrations for placenta across stage of gestation in sows. Thus, placental tissue was obtained from a total of 22 gilts on day 43, 57-58, 90-92, and 100-109 of gestation. These samples were analyzed for amino acids as described for mammary tissue. Amino acid concentrations were averaged over days in gestation to represent one amino acid profile. Amino acid values for total fluid (i.e., chorioallantoic fluid) reflect only free (not protein-bound) amino acid concentrations in the amniotic and allantoic fluids on day 45 of gestation (Wu et al., 1995). Chorioallantoic fluid amino acid profile was calculated by using an estimated 65% and 35% contribution from allantoic and amniotic fluids, respectively, to total chorioallantoic fluid. Finally, because placental protein represents approximately 96% of the total placenta + chorioallantoic fluid proteins, total (placenta + fluid) amino acid profile was estimated using 96% of placenta amino acid and 4% of chorioallantoic fluid.

There are currently no published data on amino acid concentrations of uterine tissue across stage of gestation in sows. Uterus tissue was obtained from the same gilts as described for placenta and eight additional nonpregnant gilts were used to determine amino acid concentrations in the nongravid uterus. Tissue preparation and amino acid analysis were as described for the placenta, and the amino acid across days of gestation was averaged to represent only one profile. Except for leucine and threonine, the protein amino acid composition differed between the placenta and the uterus, providing a biological basis for considering these two pools separately.

For each of the five protein pools described above, lysine content and amino acid profiles relative to lysine for the deposited protein are presented in Table 2-11. Other pools that were not accounted for but may have some effect on the prediction of amino acid requirement include mucins and immunoglobulins (Cuaron et al., 1984). Although difficult to quantify, uterine secretions contain large quantities of mucus glycoproteins that are characteristically rich in threonine (Carlstedt et al., 1983).

TABLE 2-11 Lysine Content and Amino Acid Profile of Maternal and Fetal Body Protein Gain, and of Placenta, Uterus, Chorioallantoic Fluid, Udder, and Milk Expressed as a Percentage of Lysine Content

	Maternal Body	Fetal Body	Uterus	Placenta + Fluid	Udder	Milk
	Lysine, g/100 g CP					
	6.74	4.99	6.92	6.39	6.55	7.01
Amino Acid	g Amino Acid/100 g Lysine					
Arginine	105	113	103	101	84	69
Histidine	47	36	35	42	35	43
Isoleucine	54	50	52	52	24	56
Leucine	101	118	116	122	123	120
Lysine	100	100	100	100	100	100
Methionine	29	32	25	25	23	27
Methionine + cysteine	45	54	50	50	51	50
Phenylalanine	55	60	63	68	63	58
Phenylalanine + tyrosine	97	102	—	—	—	115
Threonine	55	56	61	66	80	61
Tryptophan	13[a]	19	15	19	24	18
Valine	69	73	75	83	88	71

[a]This value is taken from the ratio of tryptophan to lysine in whole-body protein gain (12.8; Table 2-8).

Lactating Sows

Protein content of maternal body weight changes

Twelve studies (Lewis and Speer, 1973; O'Grady and Hanrahan, 1975; King et al., 1993b; Dove and Haydon, 1994; Weeden et al., 1994; Coma et al., 1996; Knabe et al., 1996; Richert et al., 1997; Dourmad et al., 1998; Touchette et al., 1998; Guan et al., 2004; dos Santos et al., 2006) were used to estimate changes in sow body protein mass during lactation, from changes in sow body weight and back fat thickness and using Eqs. 8-48 to 8-51. This information was subsequently used to estimate the contribution of lysine from mobilized body protein to lysine output with milk. Studies were selected based on providing the following: sow weight and sow backfat thickness at P2 on day 1 postpartum and weaning and lactation length. These calculations were done for each study where the parameters corresponded to either amino acid intake at marginal deficiency or to amino acid intake at excess of requirement, resulting in percentage of sow body protein loss of 9.9% and 10.1%, respectively. An average value of 10% was used to predict changes in body protein mass from changes in sow BW during lactation (Chapter 8).

Milk

Milk protein output was predicted from litter size and litter growth rate as outlined in the modeling chapter (Chapter 8). Crude protein and amino acid concentrations of milk between day 5 and 26 of lactation were based on nine studies: Elliott et al. (1971), Duée and Jung (1973), Dourmad (1991), Schneider et al. (1992a), King et al. (1993a), Csapó et al. (1996), Dourmad et al. (1998), Guan et al. (2002), and Daza et al. (2004). The basis for selecting these studies was the availability of both total milk protein nitrogen (nonprotein-nitrogen + true protein-nitrogen) and amino acid concentrations in milk for each study, or amino acids reported as a percentage of total milk protein. In addition, for studies reporting amino acid as a percentage of CP (nitrogen × 6.25) in milk, amino acid concentrations were recalculated to be expressed as a percentage of nitrogen × 6.38. The summarized lysine content in mature milk (over day 5 and 26 of lactation), along with the amino acid profile relative to lysine, is reported in Table 2-11. The average milk protein content was estimated to be 5.16% CP (N × 6.38) with a lysine content of 7.01 g/100 g milk CP.

EFFICIENCY OF AMINO ACID UTILIZATION

The Concept

The inefficiency of amino acid utilization for various body functions reflects minimum and inevitable amino acid catabolism (Moughan, 1999), as well as between-animal variation in growth performance potentials (Pomar et al., 2003). For pigs with average performance potentials, inevitable plus minimum lysine catabolism is assumed to represent 0.25 of standardized ileal digestible lysine intake, which is equivalent to a 0.75 maximum efficiency of using standardized ileal digestible lysine intake for various body functions. This efficiency is derived from observations on individual growing pigs and in well-controlled serial slaughter studies conducted between approximately 30 and 70 kg BW (Bikker et al., 1994b; Moehn et al., 2000); this efficiency seems to be independent of BW (Dourmad et al., 1996b; Moehn et al., 2000) and increases slightly with improvements in pig performance potential (Moehn et al., 2000). The inefficiency of 0.25 is applied to basal endogenous gut lysine losses and integument lysine losses to estimate the minimum contribution of lysine catabolism to urinary nitrogen excretion and, thus, maintenance lysine requirements. As mentioned previously, it has been suggested that minimum rates of amino acid catabolism be related to estimates of whole-body protein turnover (e.g., Moughan 1999; van Milgen et al., 2008). However, insufficient quantitative estimates of animal and diet effects on whole-body protein turnover and minimum amino acid catabolism are available. Estimates of minimum plus inevitable catabolism for other amino acids were obtained from carefully selected amino acid requirement studies as outlined below

To account for between-animal variation, the maximum efficiency of utilizing standardized ileal digestible lysine intake over and above maintenance requirements for protein retention was reduced (from 0.75) to match model-predicted with observed standardized ileal digestible lysine requirements obtained from empirical requirement studies. Unique adjustments were made for growing-finishing pigs (where it was associated with BW), lactating sows, and gestating sows. This proportional adjustment was applied to the other amino acids as well and kept identical across all amino acids. As a result, the ratio between efficiencies of using amino acids for maintenance and for protein retention is kept identical across all amino acids within each of the three categories of pigs (growing-finishing, gestation, lactation).

Estimates for Growing-Finishing Pigs

For growing-finishing pigs, data from 35 lysine requirement studies were used to estimate the adjustment to the efficiency of lysine utilization for body protein deposition. These studies were interpreted with the dynamic pig growth model (Chapter 8) and considering daily changes in feed intake, body weight, and body protein deposition. Based on observed levels of feed intake (assuming 5% feed wastage) and standard maintenance metabolizable energy requirements, model simulations of energy utilization were conducted to match observed with simulated BW gains, by altering the mean rate of body protein deposition. The standardized ileal digestible lysine requirements for maintenance were estimated from intestinal, skin, and hair losses and the efficiency of lysine utilization for maintenance. The standardized ileal digestible lysine requirements for protein deposition were calculated from the lysine content of protein deposition and the efficiency of lysine utilization for body protein deposition. The total standardized ileal digestible lysine requirements were then calculated as the sum of the requirements for maintenance and body protein deposition. Initially, the efficiency of utilizing standardized ileal digestible lysine intake over and above maintenance requirements for lysine retention was considered to reflect minimum and inevitable catabolism only, and thus to be identical to the efficiency of using standardized ileal digestible lysine intake for maintenance (0.75). The marginal efficiency of utilizing standardized ileal digestible lysine intake over and above maintenance requirements for lysine retention was then adjusted until a good fit between model predicted and observed lysine requirements in empirical requirement studies was achieved (Figure 2-3). These analyses revealed that the marginal efficiency of using standardized ileal digestible lysine intake for protein deposition declined with increasing BW. This efficiency was adjusted downward by 9.1% (i.e., from 0.75 to 0.682) at 20 kg BW and by 24.3% (i.e., from 0.75 to 0.568) at 120 kg BW, and extrapolated to other BW assuming a linear relationship with BW. Based on 7.1 g lysine/100 g body protein deposition, these efficiencies result in 10.4 and 12.5 g standardized ileal digestible lysine requirements per 100 g protein deposition at 20 and 120 kg BW, respectively, for pigs with typical performance potentials (e.g., maximum body protein of 145 g/day). For every 1 g increase in maximum body protein deposition, the rate of minimum plus inevitable lysine catabolism is reduced by 0.002 (Moehn et al., 2000). This is a departure from NRC (1998) where the standardized ileal digestible lysine requirement per 100 g

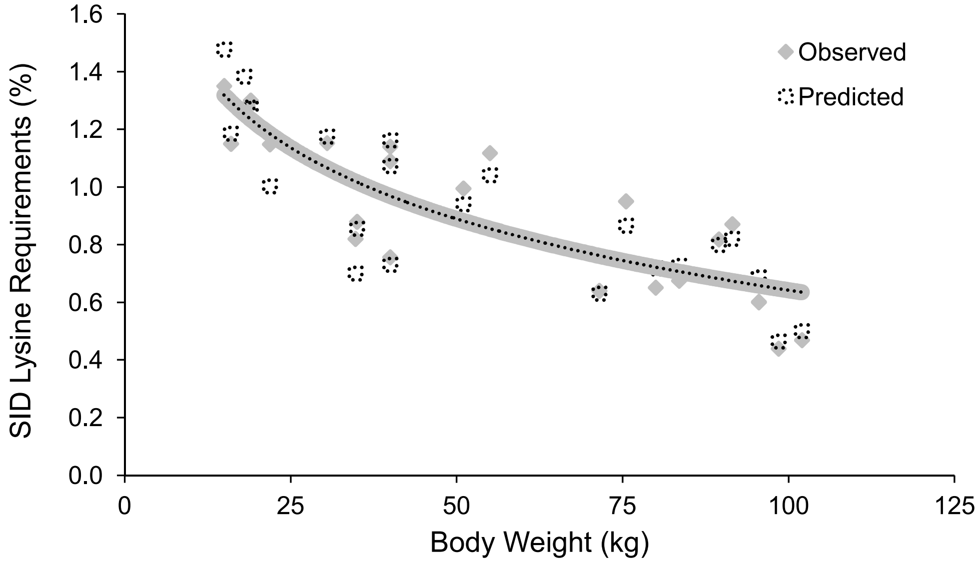

FIGURE 2-3A Standardized ileal digestible lysine requirements observed in empirical studies and predicted with the pig growth model. SOURCES: Twenty-four observations from 15 manuscripts, Martinez and Knabe (1990); Lawrence et al. (1994); Williams et al. (1998, 2 observations); Hahn et al. (1995); Dourmad et al. (1996b, 2 observations); Loughmiller et al. (1998a); Ettle et al. (2003); Urynek and Buraczewska (2003); Warnants et al. (2003, 2 observations); O'Connell et al. (2005, 3 observations; 2006, 3 observations); Yen et al. (2005); Yi et al. (2006); Kendall et al. (2008, 3 observations); Schneider et al. (2010).

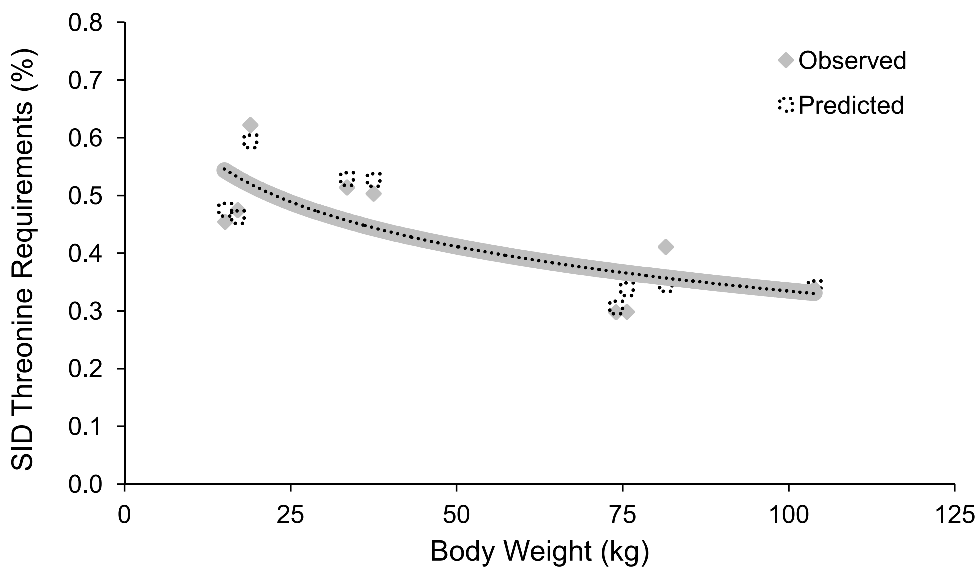

FIGURE 2-3B Standardized ileal digestible threonine requirements observed in empirical studies and predicted with the pig growth model. SOURCES: Nine observations from nine manuscripts, Cohen et al. (1977); Conway et al. (1990); Kovar et al. (1993); Sève et al. (1993); Saldana et al. (1994); Bergstrom et al. (1996); Rademacher et al. (1997); Ferguson et al. (2000); Johnston et al. (2000).

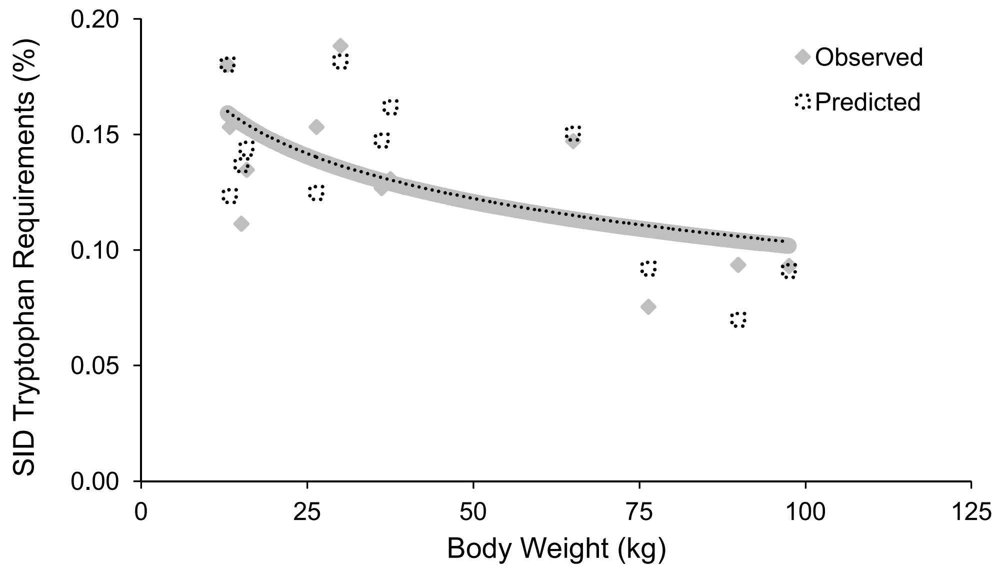

FIGURE 2-3C Standardized ileal digestible tryptophan requirements observed in empirical studies and predicted with the pig growth model. SOURCES: Twelve observations from nine manuscripts, Boomgaardt and Baker (1973); Russell et al. (1983); Borg et al. (1987); Sato et al. (1987); Burgoon et al. (1992, 2 observations); Schutte et al. (1995); Eder et al. (2001, 2003, 3 observations); Guzik et al. (2002, 2005).

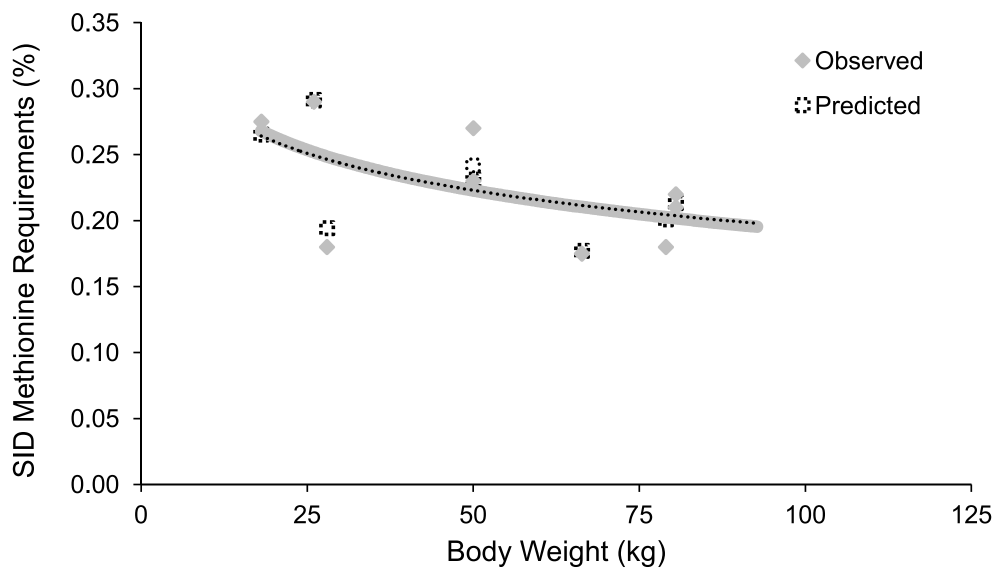

FIGURE 2-3D Standardized ileal digestible methionine requirements observed in empirical studies and predicted with the pig growth model. SOURCES: Nine observations from six manuscripts, Leibholz (1984); Chung et al. (1989); Lenis et al. (1990, 2 observations); Schutte et al. (1991); Chung and Baker (1992b); Roth et al. (2000, 3 observations).

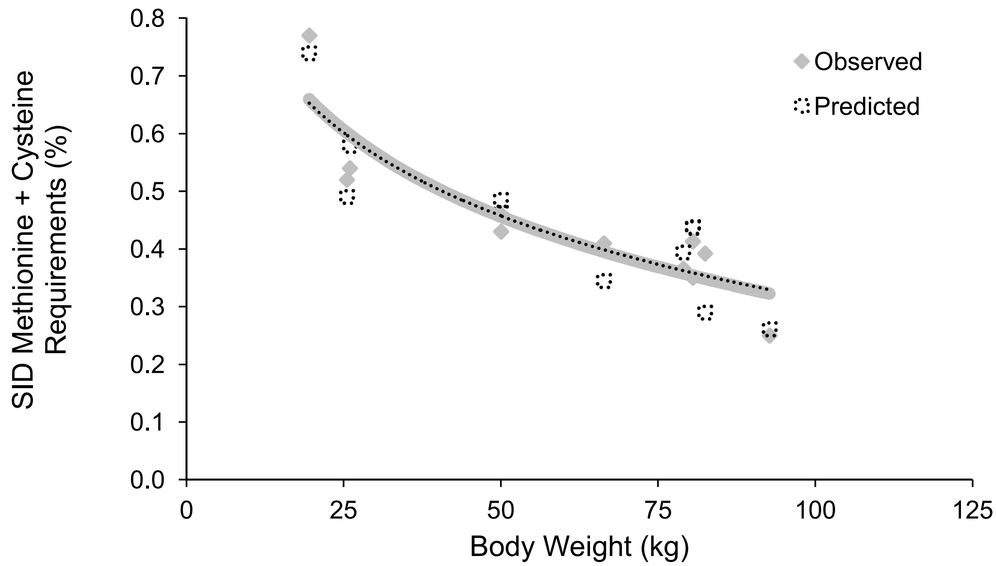

FIGURE 2-3E Standardized ileal digestible methionine + cysteine requirements observed in empirical studies and predicted with the pig growth model.
SOURCES: Eleven observations from seven manuscripts, Chung et al. (1989); Lenis et al. (1990, 2 observations); Schutte et al. (1991, 2 observations); Knowles et al. (1998); Loughmiller et al. (1998b); Roth et al. (2000, 3 observations); Yi et al. (2006).

body protein deposition was held constant across BW and pig performance potentials at 12.0 g.

Estimates of minimum plus inevitable catabolism of amino acids other than lysine were derived from experimentally determined amino acid requirements and based on concepts identical to those used for representing lysine utilization. For individual amino acids, values for minimum plus inevitable catabolism were adjusted in order to match observed amino acid requirements in empirical studies with model-predicted requirements, while adjustments to marginal efficiencies to represent effects of BW, between-animal variability, and maximum body protein deposition rates on amino acid utilization for body protein deposition (e.g., the 9.1% and 24.3% adjustment at 20 and 120 kg BW, respectively) were maintained constant across all amino acids. Figures 2-3B through E show model-predicted and observed requirements across various BW, for standardized ileal digestible threonine, tryptophan, methionine, and methionine plus cysteine, respectively.

When no reliable information was available (e.g., leucine, phenylalanine, and phenylalanine plus tyrosine), estimates of minimum plus inevitable catabolism were obtained by fitting the model to performance levels and estimates of requirements presented in NRC (1998). The resulting efficiencies of using standardized ileal digestible amino acid intakes for maintenance and growth in growing pigs at 50 kg BW are presented in Table 2-12.

Estimates for Gestating Sows

Except for lysine and threonine, there are currently no direct estimates of the efficiency of standardized ileal digestible amino acid intake utilization for amino acid retention in gestating sows, and it is not known whether these efficiencies differ among amino acids or stages of gestation. For model development, therefore, it was assumed that the efficiency of using amino acids for protein retention in various pools is identical across pools and days of gestation. The efficiency of lysine utilization for protein retention was estimated from empirical lysine requirement studies as described for growing-finishing pigs. In order to match model-predicted lysine requirements with observed requirements in three studies (Table 2-3), the maximum efficiency (equivalent to the efficiency of using lysine for maintenance; 0.75) was reduced by 34.7% to 0.49 as the estimate for the efficiency of lysine utilization for protein retention. When matching observed with predicted requirements, estimated protein retention and lysine utilization between day 90 and day 114 of gestation were considered because lysine requirements are highest during late gestation and sow performance during gestation will be most sensitive to lysine intake during this period. The value of 0.49 agrees reasonably well with that of Everts and Dekker (1995), who estimated a lysine efficiency of 0.46 at an average daily nitrogen intake of 74.4 g and 0.59 at an average daily nitrogen intake of 50.8 g in metabolism studies. Based on these analyses, for all amino acids the efficiency of using amino acids for protein retention was assumed to

TABLE 2-12 Efficiency of Dietary Standardized Ileal Digestible Amino Acid Utilization for Maintenance and for Protein Gain and Milk Protein Output in Growing-Finishing Pigs, Gestating Sows, and Lactating Sows

	Maintenance			Retention		
Amino Acid	Growing-Finishing	Gestation	Lactation	Growing-Finishing	Gestation	Lactation
Arginine	1.470	1.470	0.914	1.270	0.960	0.816
Histidine	1.000	0.973	0.808	0.864	0.636	0.722
Isoleucine	0.760	0.751	0.781	0.657	0.491	0.698
Leucine	0.751	0.900	0.810	0.649	0.588	0.723
Lysine	0.750	0.750	0.750	0.648	0.490	0.670
Methionine	0.730	0.757	0.755	0.631	0.495	0.675
Methionine + cysteine	0.603	0.615	0.741	0.521	0.402	0.662
Phenylalanine	0.671	0.830	0.820	0.580	0.542	0.733
Phenylalanine + tyrosine	0.746	0.822	0.789	0.645	0.537	0.705
Threonine[a]	0.780	0.807	0.855	0.671	0.527	0.764
Tryptophan	0.610	0.714	0.755	0.527	0.467	0.674
Valine	0.800	0.841	0.653	0.691	0.549	0.583
N × 6.25	0.850	0.850	0.850	0.735	0.555	0.759

[a]For threonine, utilization efficiencies apply to diets containing 0% fermentable fiber. Threonine utilization efficiencies decline with increasing dietary levels of fermentable fiber (Eq. 8-46).

be 34.7% lower than the efficiency for maintenance. No reliable requirement studies were deemed available to estimate the rate of minimum plus inevitable catabolism for the other amino acids and thus for the efficiency of using amino acids for both maintenance and protein retention. Therefore, efficiency values were estimated by matching model-predicted requirements with amino acid requirements for gestating sows according to NRC (1998) and with minor adjustments as detailed in Chapter 8. In this manner, efficiency values for protein retention of 0.509 and 0.402 were obtained for threonine and total sulfur amino acids, respectively. Based on metabolism studies, Everts and Dekker (1995) estimated the marginal utilization efficiencies for threonine to range between 0.44 and 0.67 and for total sulfur amino acids to range between 0.34 and 0.47; these values are in reasonable agreement with the aforementioned values. The efficiency estimates for gestation sows are presented in Table 2-12.

Estimates for Lactating Sows

To estimate the efficiency of lysine utilization for lysine output with milk, empirical lysine requirement estimates from studies presented in Table 2-4 were used. In five studies, the experimental design fit the criteria for breakpoint analyses, and therefore breakpoint analyses were performed to either confirm or adjust the reported estimated daily lysine requirement (Lewis and Speer, 1973; Chen et al., 1978; King et al., 1993b; Tritton et al., 1996; Sauber et al., 1998; Yang et al., 2000, with separate estimates of requirements for high and low lean-gain sows). For the other studies and those where the data did not conform to a breakpoint, the lysine inclusion rate value reported by the authors to yield a significant response in litter weight gain and one lysine inclusion rate value below were averaged (Lewis and Speer, 1973; O'Grady and Hanrahan, 1975; Johnston et al., 1993; Knabe et al., 1996; Tritton et al., 1996; Touchette et al., 1998). In studies where other responses were measured in addition to litter growth rate (Lewis and Speer, 1973; King et al., 1993b), such as plasma urea nitrogen, plasma amino acid concentrations, milk production, or nitrogen balance, these responses were evaluated in conjunction with the litter gain to either confirm or adjust the requirement. In some cases, lysine requirement values obtained from breakpoint analysis applied to all responses provided by a study (i.e., litter growth rate, plasma urea nitrogen, and milk production) were averaged and used as the final value for that study. Estimates were based on lactation periods with a minimum of 17 days and a maximum of 29 days. In studies where the lactation period exceeded 28 days but performance parameters were also reported for day 21, parameters based on a 21-day lactation period were used. In addition, for studies reporting estimates for specific parities (O'Grady and Hanrahan, 1975; Chen et al., 1978; Yang et al., 2000), these estimates were averaged. Others studies (Lewis and Speer, 1973) used multiple parities, which were accounted as a fixed factor in their statistical model (Johnston et al., 1993), or used first-parity sows.

The partial efficiency by which lysine in milk was derived from dietary standardized ileal digestible lysine was estimated by regression analyses (Figure 2-4). For these analyses, each of the selected lysine requirement studies was interpreted individually as outlined in detail in Chapter 8 (using Eqs. 8-70 and 8-75). Daily standardized ileal digestible lysine requirements for body maintenance functions were subtracted from daily standardized ileal digestible intake to estimate standardized ileal digestible lysine intake available for milk production. Total milk lysine output was calculated

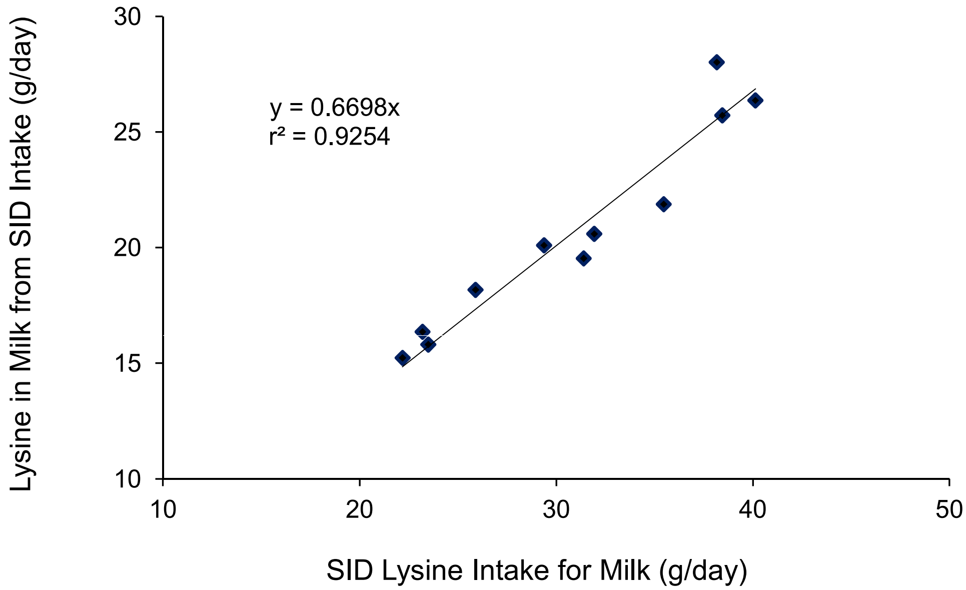

FIGURE 2-4 Relationship between estimated lysine in milk derived from SID lysine intake and estimated SID lysine intake for milk. The relationship is represented by the line and described as y = 0.6698x at zero intercept with r^2 of 0.925, where the slope of 0.6698 represents the efficiency of dietary lysine utilization into milk lysine.
SOURCES: Eleven observations from 10 manuscripts, Lewis and Speer (1973); O'Grady and Hanrahan (1975); Chen et al. (1978); Johnston et al. (1993); King et al. (1993b); Knabe et al. (1996); Tritton et al. (1996); Sauber et al. (1998, 2 observations); Touchette et al. (1998); Yang et al. (2000).

from litter size and mean BW gain of nursing pigs. When sow BW losses were observed, total milk lysine output was corrected for milk lysine derived from mobilized sow body protein. As shown in Figure 2-4, the intercept of the highly linear relationship between dietary lysine output with milk and standardized ileal digestible lysine intake available for milk production was not different from 0; the slope of this relationship was taken as the partial efficiency of standardized ileal digestible lysine intake utilization for milk production. The degree of fit of the relationship shown in Figure 2-4 is substantially better than the relationship between litter growth rate and experimentally standardized ileal digestible lysine requirements (Figure 2-5). The latter was the approach used in NRC (1998) for estimating lysine requirements of lactating sows. This improvement in fit illustrates that the more detailed interpretation of the individual lysine requirements studies results in a more accurate estimation of lysine requirements. Based on these analyses, for all amino acids the efficiency of using SID amino acid intake for milk protein production was assumed to be 10.7% lower than the efficiency for maintenance. Only for threonine and tryptophan requirements, studies (Table 2-3) were used to adjust efficiency values. For the other amino acids, efficiency values were estimated by matching model-predicted requirements with amino acid requirements for lactating sows according to NRC (1998) and with minor adjustments as detailed in Chapter 8.

Estimates of Amino Acid Requirements for Nursery Pigs

Our understanding of amino acid utilization in nursery pigs is deemed insufficient to model amino acid requirements as outlined from growing-finishing pigs. Moreover, insufficient data are available to directly relate BW to empirically determined amino acid requirements of pigs between 5 and 11 kg BW. Based on these considerations, amino acid requirements of nursery pigs between 5 and 11 kg BW were estimated based on standardized ileal digestible lysine requirements per kilogram of BW gain. Only two appropriate peer-reviewed publications about lysine requirement studies were found for pigs with an initial BW of 5 or 6 kg and a final BW of 15 kg or less, which averaged 20.1 g standardized ileal digestible lysine per kilogram of BW gain (Table 2-2). Using a larger data set of 12 studies with initial BW ranging between 5 and 13 kg (15-31 kg final BW), the average standardized ileal digestible lysine requirement per kilogram of BW gain was 19.3 g (Table 2-2). Using a constant value and its extrapolation to pigs between 5 and 11 kg has its limitations, but is supported by data from Gaines et al. (2003), Dean et al. (2007), and Nemechek et al. (2011) who reported a value close to 19 g/kg BW gain. It is acknowledged, however, that factors such as standardized ileal amino acid digestibility (Eklund et al., 2008), sources of dietary protein (Jones et al., 2011), body weight (Stein et al., 2001), or the relationship between body protein gain and BW gain in young pigs differ from those in older pigs. The current approach to estimating

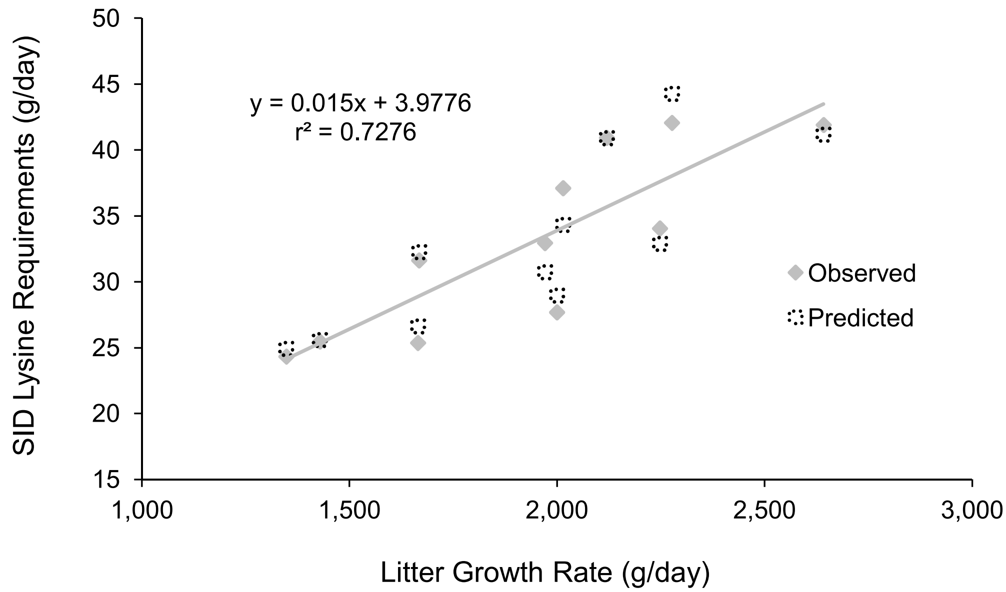

FIGURE 2-5 Relationship between standardized ileal digestible lysine requirements (standardized ileal digestible lysine estimated experimentally) and litter growth rate. The relationship is represented by the line and described as y = 0.015x + 3.9776 with an r^2 of 0.73.
SOURCES: Eleven observations from 10 manuscripts, Lewis and Speer (1973); O'Grady and Hanrahan (1975); Chen et al. (1978); Johnston et al. (1993); King et al. (1993b); Knabe et al. (1996); Tritton et al. (1996); Sauber et al. (1998, 2 observations); Touchette et al. (1998); Yang et al. (2000).

lysine requirements of nursery pigs may be refined as more information becomes available.

Requirements for standardized ileal digestible lysine were then derived by using the 19 g standardized ileal digestible lysine intake per kilogram BW gain and the estimated average daily BW gains and average daily feed intakes for 5- to 7-kg and 7- to 11-kg pigs as presented in Table 2-2. The levels of growth performance for pigs between 5 and 11 kg BW reflect slightly better than average levels of performance of nursery pigs (Meisinger, 2010). The standardized ileal digestible lysine requirement of pigs between 11 and 25 kg BW in Table 2-2 represents an average from empirical studies of lysine requirements that used pigs with a range of initial body weights from 9 to 13 kg (19 to 31 kg final BW). Following the establishment of standardized ileal digestible lysine requirements for pigs in the weight categories 5-7, 7-11, and 11-25 kg, requirements for other amino acids were calculated using weight-specific extrapolations of maintenance amino acid requirements and optimum amino acid ratio in whole-body protein gain as described previously and in Chapter 8.

Estimates of Amino Acid Requirement of Breeding Boars

Energy, amino acid, mineral, and vitamin requirements of developing and adult boars were reviewed by Kemp and Soede (2001). Adult boars constitute a relatively small part of commercial swine enterprises, and less is known about their amino acid requirements than is known for growing pigs, or gestating and lactating sows. The previous edition of this publication (NRC, 1998) listed the lysine requirement of sexually active boars as 0.60% of the diet or 12.0 g/day total lysine (an assumed feed intake of 2 kg/day). This requirement was based on studies (Meding and Nielsen, 1977; Yen and Yu, 1985; Kemp et al., 1988; Louis et al., 1994a,b) in which sperm production and semen quality were measured. More recently, Rupanova (2006) reported that boars fed a diet containing 1.03% lysine had better semen quality, with no change in ejaculate volume, than boars fed a diet with 0.86% lysine. However, this was a limited study with only 10 boars (5 per group) and a 46-day experimental period. Another report (Golushko et al., 2010) indicated a requirement of 0.92% lysine (0.76% digestible lysine), but few experimental details are provided. Thus, although it is possible that boars may benefit from lysine concentrations > 0.60%, there is insufficient evidence to change the previous NRC (1998) estimate of the requirement. Requirements for the other essential amino acids were estimated using the amino acid profile for sow maternal body protein (Table 2-11).

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3

Lipids

INTRODUCTION

Although the terms "fats" (solid triacylglycerols) and "oils" (liquid triacylglycerols) are sometimes used interchangeably, the term "lipids" generally refers to all materials that dissolve in a fat-solubilizing solvent and may include sterols; waxy esters; mono-, di-, and triacylglycerols; phospholipids; glycolipids; free fatty acids; long-chain aldehydes and alcohols; fat-soluble vitamins; and other nonpolar products. Fat, together with its constituent fatty acids, serves many important roles within swine diets (Azain, 2001; Gu and Li, 2003; Rossi et al., 2010; Lin et al., in press). Attributes of dietary fat include:

- provides a dense source of energy,
- provides essential fatty acids,
- produces low heat increment,
- facilitates absorption of fat-soluble vitamins,
- lubricates during pelleting,
- reduces feed dust, and
- lubricates during mastication and swallowing.

Fat is a natural constituent of many ingredients that are commonly fed to swine (Table 17-1), and it also may be explicitly supplemented into diets via concentrated sources (Table 17-4). While dietary fat provides essential fatty acids as required nutrients, the decision to supplement swine diets with fat is driven largely by economics, namely the cost per unit of energy provided. Considering diet-handling characteristics, the practical upper limit to fat supplementation in typical diets is ~6% added fat, but this can be increased by postpellet spray application. Increased energy density of diets containing supplemental fat typically reduces feed intake (kg/day) thereby improving feed efficiency (G:F; Engel et al., 2001), but requires careful formulation to maintain a proper nutrient:energy ratio to ensure that nutrient requirements are met. Furthermore, the fatty acid composition of dietary fat can directly alter pork fatty acid composition and thereby affect pork quality (for reviews, see Warnants et al., 2001, and Wood et al., 2008). Supplemental fats are subject to oxidative decay which can reduce nutritional value, so prudent attention to fat quality indexes is warranted. These elements are discussed in the following review. Fat-soluble compounds in the environment (pesticides, etc), as discussed in Chapter 11, can localize within dietary lipids, increasing their risk of contamination.

DIGESTIBILITY AND ENERGY VALUE OF LIPIDS

Fats and oils are generally considered to be highly digestible energy sources (Babatunde et al., 1968; Cera et al., 1988a,b, 1989a, 1990; Li et al., 1990; Jones et al., 1992; Jorgensen et al., 1996; Jorgensen and Fernandez, 2000), with the apparent digestibility of short- or medium-chain fatty acids (14 carbons or less) ranging from 80 to 95%, regardless of the dietary ratio of unsaturated:saturated (U:S) fatty acids (Stahly, 1984; Cera et al., 1990). Source, inclusion level, and intermolecular distribution of the saturated and unsaturated fatty acids within lipids may affect lipid digestibility and metabolism (Allee et al., 1971, 1972; Mattson et al., 1979; Jorgensen et al., 1996; Averette Gatlin et al., 2005; Duran-Montgé et al., 2007) as well as nitrogen utilization and amino acid absorption (Lowrey et al., 1962; Cera et al., 1988a, 1989a,b; Li et al., 1990; Li and Sauer, 1994; Jorgensen et al., 1996; Jorgensen and Fernandez, 2000; Cervantes-Pahm and Stein, 2008). In general, the apparent digestibility of various lipids in nursery pigs increases with age (Hamilton and McDonald, 1969; Frobish et al., 1970) and U:S ratio (Powles et al., 1995), with digestibility of animal fat sources (lard and tallow) increasing to a greater extent with age of the animal compared to digestibility of vegetable oils (Cera et al., 1988a,b, 1989a, 1990). Relative to differences in digestibility between fat types, saturated lipids are less digestible than unsaturated lipids (Wiseman et al., 1990; Powles et al., 1994), although this is not a consistent conclusion (Jorgensen and Fernandez, 2000; Kerr et al., 2009; Kil et al., 2010a). Of notable consequence is the negative impact of free fatty acids on lipid digestibility. Brambila and Hill (1966) and Jorgensen and Fernandez (2000) reported that digestibility of free fatty acids is lower than that of triacylglycerides, which coincides with a lower digestible energy content with increasing levels of free fatty acids (Wiseman and Salvador, 1991; Powles et al., 1994, 1995; Jorgensen and Fernandez, 2000). In contrast, fatty acid digestibility was not affected by free fatty acid level in choice white grease (DeRouchey et al., 2004) or by feeding soybean soapstock (Atteh and Leeson, 1985). In addition, apparent fat digestibility decreases by 1.3-1.5% for each additional 1% of crude fiber in the diet (Just, 1982a,b,c; Dégen et al., 2007). Most recently, Kil et al. (2010b) showed that the feeding of added fat induced smaller increments in endogenous fat loss than inherent fat and that purified neutral detergent fiber had little effect on apparent or true fat digestibility.

Table 17-4 estimates the DE content of various fat sources based on the research by Wiseman et al. (1990) and Powles et al. (1993, 1994, 1995), using the equation

$$\text{DE, kcal/kg} = \{36.898 - [0.005 \times \text{FFA, g/kg}] - [7.330 \times \exp(-0.906 \times \text{U:S})]\} / 4.184 \quad \text{(Eq. 3-1)}$$

where FFA = free fatty acid and U:S = unsaturated:saturated fatty acid ratio.

Metabolizable energy was subsequently calculated as 98% of DE, and NE was estimated at 88% of ME (van Milgen et al., 2001). Although recent research (Jorgensen and Fernandez, 2000; Kerr et al., 2009; Silva et al., 2009; Anderson et al., 2012) has shown that the DE and ME contents of various refined lipids were similar to values reported in NRC (1998), the accuracy of using these equations to predict the energy content of all types and qualities of fats is not known. In addition, DE and ME systems do not account for the energetic efficiency of metabolizing dietary lipids and may underestimate their NE (Noblet et al., 1993; de Lange and Birkett, 2005). The NE estimate of 4,180 kcal/kg for tallow (Galloway and Ewan, 1989), a lower than expected marginal efficiency of utilization of unsaturated fat for body fat (Halas et al., 2010), and the recent NE estimate for soybean oil (4,679 kcal/kg) and choice white grease (5,900 kcal/kg) (Kil et al., 2010a) are substantially less than the 7,120 kcal/kg for both lipids as suggested by Sauvant et al. (2004), and lower than would be expected when considering the efficiency of ME for NE is assumed to be high (Just, 1982d; Noblet et al., 1993; Jorgensen et al., 1996). This discrepancy, combined with a lack of the understanding of the interactive effects between fatty acid composition, free fatty acid level, and degree of oxidation on DE, ME, and NE, necessitates a better understanding of NE values of various lipid products.

DIETARY FAT AND PERFORMANCE THROUGHOUT THE LIFE CYCLE

The value of adding fat to the diets of weanling pigs remains uncertain (see Gu and Li, 2003, for review). Pettigrew and Moser (1991) summarized data involving 92 comparisons of fat additions for pigs from 5 to 20 kg. In this weight range, addition of fat reduced feed intake and improved G:F. Similarly, fat encapsulation via spray-drying and fat emulsification (Xing et al., 2004) has yielded only modest improvements in utilization. Inconsistent responses to added fat may be a result of a number of factors, including the age of the pig, the amount of fat added, the type of fat, and the method by which the fat was added. Pettigrew and Moser (1991) reported responses for studies in which a constant protein:energy ratio was maintained and found no response in growth rate, a reduction in feed intake, and an improvement in G:F when fat was added.

For growing-finishing swine (20-100 kg), fat supplementation generally improved growth rate, reduced feed intake, and improved G:F, but increased backfat thickness (Coffey et al., 1982; Pettigrew and Moser, 1991; Øverland et al., 1999; Benz et al., 2011a). Chiba et al. (1991) reported that a ratio of 3.0 g of lysine (or 49 g of balanced protein) per megacalorie of DE was necessary to maximize the beneficial effects of fat addition to diets. The digestibility of the dietary fat, quantity of ME and fat consumed, and environmental temperature in which pigs are housed influence the nutritional value of fat as an energy source for pigs (Stahly, 1984). In general, the substitution of fat for carbohydrate energy in a diet for pigs maintained in a thermoneutral environment increases growth rate and decreases the ME required per unit of body weight gain. But for pigs housed in a warm environment, voluntary ME intake increases by 0.2-0.6% for each additional 1% of fat added to the diet. This increase is because the heat increment of fat is less than that of carbohydrate (Stahly, 1984).

Evidence suggests that the addition of fat to the diets of sows during late gestation or lactation increases milk yield, fat content of colostrum and milk, and pig weight gain and survival from birth to weaning, especially of low-birth-weight pigs (Moser and Lewis, 1980; Boyd et al., 1982; Coffey et al., 1982; Seerley, 1984; Pettigrew and Moser, 1991; Averette et al., 1999; Quiniou et al., 2008). Improvements in survival of pigs from birth to weaning were dependent on the total amount of fat the sow consumed before farrowing (> 1,000 g) and the birth-to-weaning survival of the control groups (< 80%). Direct oral supplementation of medium-chain triacylglycerides to low-birth-weight suckling pigs also may improve survival (Lepine et al., 1989; Odle, 1997; Casellas et al., 2005; Dicklin et al., 2006). Fat supplementation can reduce sow weight loss during lactation and decrease the interval from weaning to mating (Moser and Lewis, 1980; Pettigrew, 1981; Cox et al., 1983; Seerley, 1984; Moser et al., 1985; Shurson et al., 1986; Pettigrew and Moser, 1991;

Averette Gatlin et al., 2002a). Most recently, Rosero (2011) and Rosero et al. (2012) conducted dose-response studies (0, 2, 4, and 6% added fat) in modern, prolific sows using either choice white grease or an animal-vegetable blended fat. Choice white grease reduced sow weight loss and promoted litter weight gain in a dose-response manner, whereas the animal-vegetable blend fat did not. Both fats promoted a rapid return to estrus after weaning and improved farrowing rate after mating. Improved reproduction may be attributed to the provision of essential fatty acids (discussed below).

DIETARY ESSENTIAL AND BIOACTIVE FATTY ACIDS

In addition to providing a dense source of energy, selected fatty acids are known to be essential, bioactive nutrients, influencing many important physiological processes, including lipid metabolism, cell division and differentiation, and immune function and inflammation. Originally, linoleic and arachidonic acids were both identified as dietary essential fatty acids (EFAs; Cunnane, 1984). Now it is recognized that these fatty acids are members of the n-6 series of EFAs and that arachidonic acid can be synthesized in vivo from linoleic acid via the sequential action of Δ^6-desaturase, elongase, and Δ^5-desaturase (Figure 3-1; Jacobi et al., 2011). In addition to EFAs of the n-6 series, pigs require EFAs of the n-3 series (α-linolenate, eicosapentaenoate, and docosahexaenoate; see Palmquist, 2009, for review). Similar to the n-6 fatty acids, very-long-chain n-3 polyunsaturated fatty acids can be synthesized from dietary α-linolenate, and typical swine diets likely contain adequate amounts of this fatty acid; however, definitive data are lacking.

The high ratio of n-6:n-3 fatty acids contained in typical swine diets is a potential concern. Because the 18-carbon precursor fatty acids compete within the elongation/desaturation pathway (Figure 3-1), this imbalance may limit the production of anti-inflammatory eicosanoids derived from eicosapentaenoic acid (see Wall et al., 2010, for review). Despite this potential imbalance, it is difficult to produce overt signs of an EFA deficiency in pigs. For example, Enser (1984) reported normal growth in pigs from weaning to slaughter weight when they were fed diets containing only 0.1% linoleic acid. The Agricultural Research Council (1981) suggested the EFA requirements are 3.0% of dietary DE for pigs up to 30 kg and 1.5% of dietary DE from 30 to 90 kg. These are equivalent to about 1.2 and 0.6% of the diet. Christensen (1985) reported that for maximum performance and efficiency of feed utilization, pigs weaned at 5 weeks of age and raised to 100 kg BW require a dietary linoleic acid of 0.2% of GE, or about 0.1% of the diet. As such, adequate amounts of linoleic and α-linolenic acids are usually present in diets based on commonly used cereal grains and protein supplements. There is some evidence that flux through the elongation/desaturation pathway is limited, especially in young animals. Accordingly the FDA approved the addition

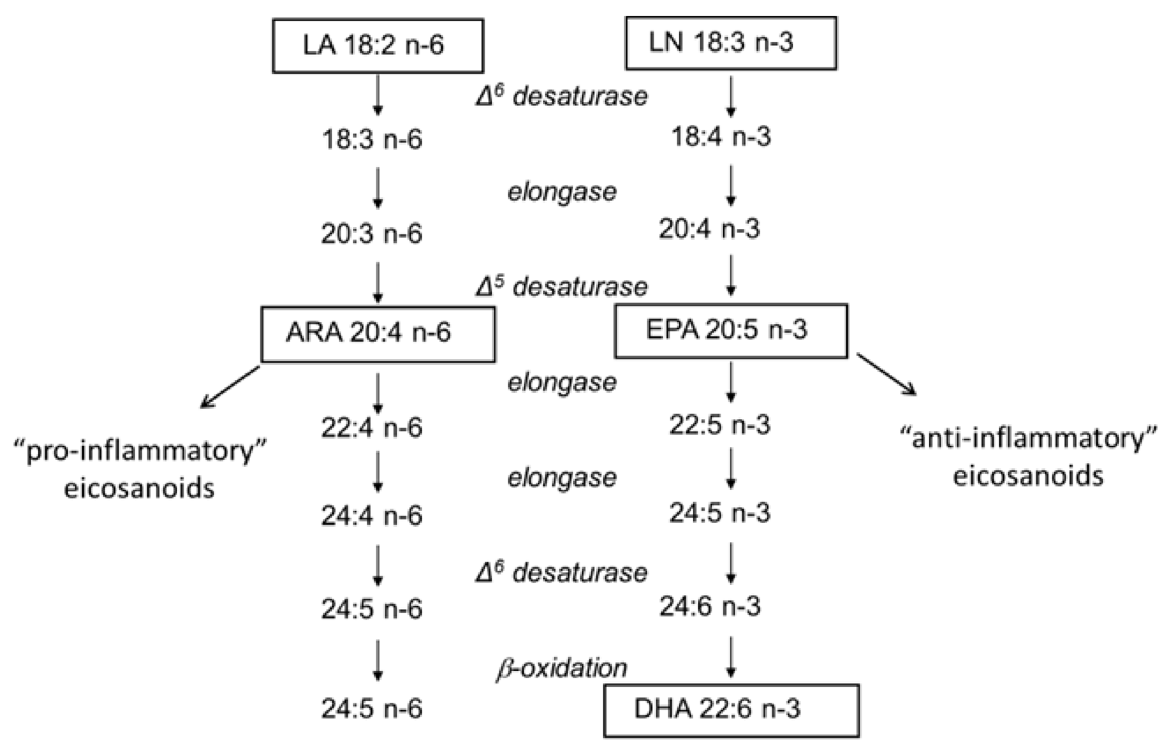

FIGURE 3-1 Synthesis of long-chain polyunsaturated fatty acids from C18 precursors. LA, linoleic acid; ARA, arachidonic acid; LN, α-linolenic acid; EPA, eicosapentaenoic acid; DHA, docosahexaenoic acid. Adapted from Nelson (2000).

of arachidonic and docosahexaenoic acids (up to 1.25% of dietary fat) to human infant formulas in 2002, predicated in part on research conducted with suckling pigs (Huang et al., 2002; Mathews et al., 2002). In addition, research has examined effects of n-3 rich marine oils on reproduction in boars (Penny et al., 2000; Rooke et al., 2001a; Estienne et al., 2008; Castellano et al., 2010) and sows (Perez Rigau et al., 1995; Rooke et al., 2001b; Laws et al., 2007; Brazle et al., 2009; Gabler et al., 2009; Mateo et al., 2009; Papadopoulos et al., 2009; de Quelen et al., 2010; Cools et al., 2011; Leonard et al., 2011; Smits et al., 2011), and while tissue n-3 enrichment is consistently observed, measurable positive effects are inconsistent. Furthermore, most studies lack sufficient dose-response data on which to base a quantitative dietary recommendation. Effects of supplemental n-3 fatty acids on immune response in young pigs also have been documented (Fritsche et al., 1993; Turek et al., 1996; Thies et al., 1999; Carroll et al., 2003; Liu et al., 2003; Jacobi et al., 2007; Lauridsen et al., 2007; Binter et al., 2008) but, again, dose-response data are generally lacking.

Because pork fatty acid composition may be readily altered via dietary means, researchers have investigated enrichment with various fatty acids including oleic (Miller et al., 1990), conjugated linoleic (Averette Gatlin et al., 2002c, 2006; Dugan et al., 2004; Weber et al., 2006; Martin et al., 2007; Latour et al., 2008; Jiang et al., 2009; Larsen et al., 2009; White et al., 2009; Cordero et al., 2010), and n-3 fatty acids (see Palmquist, 2009, for review; Bryhni et al., 2002; Duran-Montgé et al., 2008; Flachowsky et al., 2008; Huang et al., 2008; Jaturasitha et al., 2009; Meadus et al., 2010; Realini et al., 2010; Wiecek et al., 2010) as an alternate route to supply bioactive lipids into the human food supply. While the half-life of α-linolenate in pork fat has been estimated to exceed 300 days (Anderson et al., 1972), measurable changes in fatty acid composition of some fat depots can be detected in modern genotypes in as little as 2 weeks after a dietary alteration (Averette Gatlin et al., 2002b). Mathematical models have been developed to describe relationships between diet fatty acid composition and the corresponding enrichment of pork (Lizardo et al., 2002; Nguyen et al., 2003).

DIETARY FAT, IODINE VALUE, AND PORK FAT QUALITY

It has been known for many years that dietary fatty acid composition directly affects pork fatty acid composition. In 1926, Ellis and Isbell documented the increase in unsaturated fatty acid content of lard from pigs consuming various unsaturated oils. Indeed, as described above, this can be exploited to enrich pork with bioactive fatty acids for health-conscious consumers. However, elevated polyunsaturated fatty acid content of pork also presents challenges with processing of pork containing "soft fat" (e.g., belly slicing efficiency into bacon; fat smearing) and reduced shelf life resulting from oxidative rancidity (see Apple, in press, for review). These problems are exacerbated when feeding ingredients rich in unsaturated fats, such as dried corn distillers grains with solubles (DDGS) (White et al., 2009; Xu et al., 2010).

Belly-processing challenges stemming from elevated content of unsaturated fatty acids are accentuated in lean genotypes, and researchers have investigated multiple dietary approaches for abrogating the problem such as (1) feeding naturally saturated fats such as tallow (Averette Gatlin et al., 2002b; Apple et al., 2009), (2) feeding chemically hydrogenated fats (Averette Gatlin et al., 2005), (3) switching cereal grains (Carr et al., 2005; Lampe et al., 2006), and (4) feeding conjugated linoleic acid (Thiel-Cooper et al., 2001; Wiegand et al., 2001; Averette Gatlin et al., 2002c, 2006; Dugan et al., 2004; Weber et al., 2006; Martin et al., 2007; Latour et al., 2008; Jiang et al., 2009; Larsen et al., 2009; White et al., 2009; Cordero et al., 2010). Conjugated linoleic acid (CLA) may inhibit stearoyl-CoA desaturase, thereby diminishing the de novo synthesis of C16:1 and C18:1and concomitantly increasing the concentrations of C16:0 and C18:0 (Demaree et al., 2002; Averette Gatlin et al., 2002c). Accordingly, CLA may be combined with unsaturated dietary fats to lessen the negative impact on pork fat quality (Larsen et al., 2009). Several studies have demonstrated that addition of CLA to diets of both neonatal and growing-finishing pigs decreases fat deposition (Ostrowska et al., 1999, 2003; Thiel-Cooper et al., 2001; Corl et al., 2008).

A practical means to manage the problem of soft pork fat is to formulate diets based on the iodine value (IV) of the dietary fat. Iodine value is a chemical measure of the grams of iodine bound per 100 g of fat, and it is a crude measure of the relative content of double bonds within the constituent fatty acids. The higher the IV, the more unsaturated and softer the fat. The IV can be determined directly (AOAC, 1997) or it may be estimated stoichometrically via gas chromatography of fatty acid methyl esters (FAME) derived from the fat according to the following equation:

$$IV = \sum 100 \times \frac{FAME_i \times 253.81 \times db_i}{MW_i} \quad \text{(Eq. 3-2)}$$

where $FAME_i$ = the proportion of fatty acid methyl ester of the ith fatty acid in the mixture, 253.81 is the molecular weight of I_2, db_i = number of double bonds in the ith fatty acid, and MW_i is the molecular weight of the ith FAME (AOCS, 1998; Knothe, 2002; Pétursson, 2002; Meadus et al., 2010).

This translates, on a fatty acid basis, to

$$\begin{aligned}\text{Total IV}_{\text{fatty acid basis}} = \% \text{ C16:1 } (0.9976) \\ + \% \text{ C18:1 } (0.8985) \\ + \% \text{ C18:2 } (1.8099) + \% \text{ C18:3 } (2.7345) \\ + \% \text{ C20:1 } (0.8173) \\ + \% \text{ C20:4 } (3.3343) + \% \text{ C20:5 } (4.1956) \\ + \% \text{ C22:1 } (0.7496) \\ + \% \text{ C22:5 } (3.8395) + \% \text{ C22:6 } (4.6358)\end{aligned} \quad \text{(Eq. 3-3)}$$

and expressed on a pure triacylglyceride acid basis it equates to:

$$\text{Total IV}_{\text{triacylglyceride basis}} = \%\ \text{C16:1}\ (0.9502) + \%\ \text{C18:1}\ (0.8598) + \%\ \text{C18:2}\ (1.7315) + \%\ \text{C18:3}\ (2.6152) + \%\ \text{C20:1}\ (0.7852) + \%\ \text{C20:4}\ (3.2008) + \%\ \text{C20:5}\ (4.0265) + \%\ \text{C22:1}\ (0.7225) + \%\ \text{C22:5}\ (3.6974) + \%\ \text{C22:6}\ (4.4632) \qquad \text{(Eq. 3-4)}$$

where % is the percentage that each FAME represents of the sum total of all FAME in the gas chromatographic analysis.

Tables 17-1 and 17-4 contain estimates of IV of several ingredients based on their fatty acid composition using the coefficients of Eq. 3-2 and fatty acid concentrations expressed as a percentage of total ether extract. By way of example, it is worth noting that the IV of raw corn oil as it exists in corn (a value of 107 from Table 17-1) is considerably lower than the IV of purified corn oil (a value of 125 from Table 17-4; USDA, 2011). The reason for this stems from the presence of phospholipids and other lipid constituents in raw corn oil that are removed by the bleaching process when the oil is purified (www.corn.org). Such constituents in the raw oil effectively reduce the IV. The tables also contain the iodine value product (IVP) (Madsen et al., 1992), which is the product of IV and the content of fat in the ingredient (multiplied by a scaling factor of 0.1):

$$\text{IVP} = (\text{IV of ingredient fat}) \times (\%\ \text{fat in the ingredient}) \times (0.1) \qquad \text{(Eq. 3-5)}$$

The utility of IVP is that it can be used in diet formulation to predict carcass IV (Cast, 2010). Specifically, the following regression equations allowing the prediction of carcass IV from dietary IVP have been developed:

$$\text{Carcass IV} = 47.1 + 0.14 \times \text{dietary IVP};\ r^2 = 0.86\ \text{(Madsen et al., 1992)} \qquad \text{(Eq. 3-6)}$$

$$\text{Carcass IV} = 52.4 + 0.32 \times \text{dietary IVP};\ r^2 = 0.99\ \text{(Boyd et al., 1997)} \qquad \text{(Eq. 3-7)}$$

Differences in the prediction equations are attributed to the range in IVP spanned and heavier-weight animals allowed ad libitum access to feed in the research by Boyd et al. (1997). Because of the differences in prediction equations and because there was insufficient information to establish robust quantitative relationships between diet fat IVP and carcass fat IV values, these concepts were not incorporated into the computer model. A most recent effort (Benz et al., 2011b) to validate diet formulation based upon IVP concluded that dietary C18:2n-6 content was a better predictor of carcass IV than was IVP.

CARNITINE

Carnitine is a conditionally essential nutrient that is needed to transfer long-chain fatty acids across the inner mitochondrial membrane for subsequent oxidation. Pigs and other mammals can synthesize carnitine from lysine, but there is evidence that young pigs may not always be able to synthesize sufficient quantities (van Kempen and Odle, 1993; Owen et al., 1996; Heo et al., 2000a,b; Lyvers-Peffer et al., 2007). Carnitine can, therefore, be added to diets fed to pigs in the form of L-carnitine. Addition of carnitine to diets fed to weanling pigs may improve pig performance (Owen et al., 1996), but that is not always the case (Hoffman et al., 1993; Owen et al., 2001). Carnitine also does not appear to improve growth performance of growing-finishing pigs (Owen et al., 2001). However, addition of carnitine to diets fed to sows may improve fetal metabolism (Xi et al., 2008) and size (Brown et al., 2008) and increase the number of live-born piglets (see Eder, 2010, for a review; Musser et al., 1999b; Ramanau et al., 2002), although that is not always the case (Musser et al., 1999a). However, piglets born to sows fed carnitine sometimes have improved weaning weight (Ramanau et al., 2004).

QUALITY MEASURES OF DIETARY FAT

Oxidation of lipids leads to the formation of primary, secondary, and tertiary oxidation products that impart undesirable odors and flavors associated with rancidity and, therefore, are important components in determining the nutritional value and/or the shelf life of a variety of feedstuffs. Lipids can be oxidized by the catalytic action of enzymes or oxygen radicals on lipids, with the process consisting of: (1) formation of free lipid radicals, initiating the oxidation process; (2) formation of hydroperoxides as primary reaction products; (3) formation of secondary oxidation products; and (4) formation of tertiary oxidation products (AOCS, 2005). The rate of lipid oxidation primarily depends on the degree of saturation, with polyunsaturated lipids (i.e., di- and triunsaturated acids) being more rapidly oxidized than monounsaturated lipids, with saturated lipids being almost stable. Oxidation rate also increases with increasing temperature, oxygen pressure, and irradiation. It can be catalyzed by heavy metals and undissociated salts, with water and various nonlipidic components affecting the process as well (AOCS, 2005). Not only can the production of these oxidative products affect the production of off-flavors and odors (rancidity), but the formation of hydroperoxides and their breakdown products can also interact with other nutrients or cellular components (proteins, membranes, and enzymes) and affect cell functions within the animal (Comporti, 1993; Frankel, 2005).

Measurement of lipid oxidation is a complex task. Oxidation reactions occur concurrently whereby a wide range of oxidative compounds are produced and modified during the oxidation process (Figure 3-2). As such, the determination of oxidative stability indexes in the laboratory may not give an accurate indication of the current oxidation status or the predicted shelf life of the feedstuff (lipid) in question. Although some of the more common analytical methods are briefly described below, there is no single method that is universally accepted as the best measure of lipid oxidation, and in many cases, several methods may be needed to provide a reliable estimate of the current and projected oxidation status of a lipid.

Traditional Analytical Tests (Current Oxidation Status)

Peroxide value (PV) provides an estimation of hydroperoxides (including their oxidation into dihydroperoxide and cyclic peroxides) and is considered as an estimate of the formation of primary lipid oxidation products, but because peroxides decompose to secondary products rapidly, this value can result in an underestimation of the true degree of oxidation (Ross and Smith, 2006). Not only can numerous factors affect the determined PV, but also the results can be expressed in different ways, most often as milliequivalents per kilogram, but possibly as millimoles per kilogram (which equates to 50% of the milliequivalents per kilogram value) or as milligrams of active oxygen per kilogram (which equates to 8 times higher than the milliequivalents per kilogram value), which adds confusion in interpreting published data.

Carbonyl compounds, namely aldehydes and ketones, and their oxidation products or epoxides (oxirane derivatives) are some of the most reactive lipid oxidation products formed by the decomposition of lipid hydroperoxides, and have been suggested as important markers of lipid oxidation. Although benzidine value (BV) and para-anisidine value (AV) methodologies are similar and the structures of the condensation products produced are comparable, differences remain in the length of the conjugated double bonds such that the absolute values by the two methods differ. Likewise, the conjugated-double-bond compound produced by the reaction of 2-thiobarbituric acid (TBA) with malonaldehyde (malonaldehyde is produced during the oxidation of polyunsaturated fatty acids or unsaturated aldehydes) can be considered another indicator of lipid oxidation. However, because TBA reacts with many compounds in addition to malonaldehyde, studies using the TBA test report results in terms of thiobarbituric reactive substances (TBARS) and not only with malonaldehyde, which can lead to an overestimation of the extent of lipid oxidation (Ross and Smith, 2006). Although it has been suggested that it would be desirable to replace TBARS with GC (gas chromatography) and HPLC (high-performance liquid chromatography) methodology (Frankel, 2005; Ross and Smith, 2006), TBARS is one of the most common methods for assessing lipid oxidation and is simple, rapid, relatively cheap, and suitable for running a large number of analyses. Because of the limitations of TBARS, the measurement of specific volatile compounds has become a popular indictor of lipid oxidation. Of the secondary oxidation products of hydroperoxides (alkanes, alkenes, aldehydes, ketones, alcohols, esters, acids, and hydrocarbons), aldehydes (octanal, nonanal, pentanal, and hexanal) are the most prominent volatiles produced with hexanal, and are considered one of the best indicators of lipid oxidation (Ross and Smith, 2006). Hydroxylated aldehydes can also act as mediators of various biological effects of aldehydes, with 4-hydroxy-2-nonenal (4-HNE) considered one of the best-characterized hydroxylated aldehydes because of its adverse physiological effects (Seppanen and Sarri Csallay, 2002; Poli et al., 2008). Like many compounds, 4-HNE can be measured by a variety of methods with different levels of reliability (Uchida et al., 2002; Zanardi et al., 2002). The analytical methods described above are used to determine the

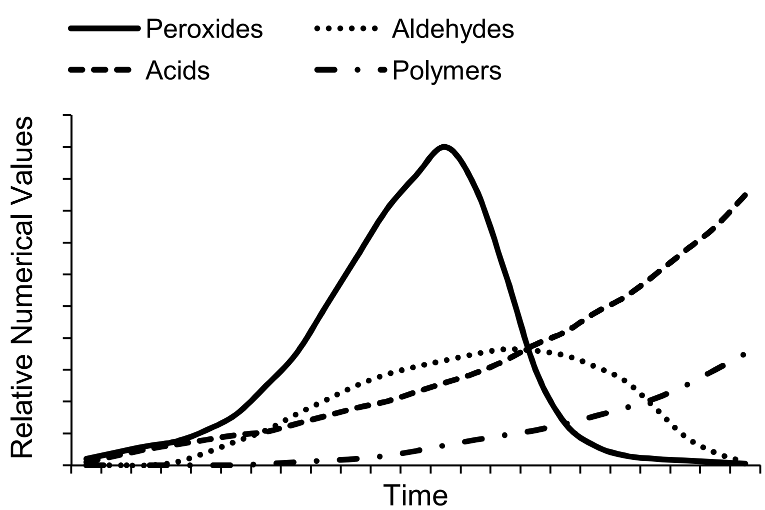

FIGURE 3-2 Composite changes in selective oxidative products during oxidation of lipids. Adapted from Liu (1997).

sensitivity of lipids to oxidation and provide a rough indicator of lipid quality. They do not, however, provide information on the changes in the oxidative status of the samples in the future (i.e., projected shelf life).

Accelerated Stability Tests (Predictive Measures)

To estimate shelf life, accelerated tests have been developed to allow predictions of oxidative stability of the product as a function of time. The most common accelerated stability tests expose the sample to increased temperature and elevated oxygen pressures. The Schaal Oven test involves heating a lipid sample to 50-60°C with the endpoint of oxidation determined by sensory characteristics or by an endpoint PV or TBA value. Although well correlated with actual shelf-life predictions, this method is relatively time- and labor-consuming for a routine method. The active oxygen method (AOM) bubbles purified air through a lipid sample held at 97.8°C, and PV is plotted over time to determine the time required to reach a PV of 100 mEq/kg fat. The AOM is also time- and labor-consuming, having several inherent deficiencies such that results can be variable. The oxidative stability index (OSI) was developed as an alternative for the AOM test and is based upon the principle that as lipids are oxidized (temperature and air), volatile acids will be formed and transferred with the air passing through the sample and collected in a detection cell containing deionized water, which is continuously measured for conductivity by automated software. Relative to the AOM test, the advantages of the OSI test include that it is a more accurate detection of the oxidation induction point, is less sensitive to the airflow, is based on stable tertiary oxidation products, is a more reproducible test, and is fully automated (Shahidi and Wanasundara, 1996).

Modulation of Lipid Oxidation

The oxidative stability of diets containing unsaturated fatty acids should be carefully considered since the resulting oxidation products can adversely affect other nutrients (such as vitamin E; Mahan, 2001) and reduce animal performance (described below). Controlling lipid oxidation is based on the fundamental understanding of lipid oxidative processes. Thus, partial hydrogenation, reduced linolenic fatty acid content, reduced exposure to oxygen (nitrogen blanketing), addition of metal inactivators (citric and phosphoric acid), protection from UV radiation (dark containers or limited "contamination" with chlorophyll), temperature reduction, and addition of antioxidants have been evaluated as potential methods to reduce the rate of oxidation (Frankel, 2007). Synthetic (e.g., ethoxyquin, butylated hydroxyanisole [BHA], butylated hydroxytoluene [BHT], propyl gallate [PG[, and tert-butylhydroquinone [TBHQ]) and natural (e.g., tocopherols and carotenoids) antioxidants, plant extracts, and chelating compounds (e.g., ascorbic acid, citric acid, flavonoids, phosphoric acid, ethylenediaminine tetraacetic acid-EDTA, and 8-hydroxyquinoline) have been used in the feed and food industry to inhibit lipid oxidation and retard the development of rancidity in foods (Frankel, 2005, 2007; Wanasundara and Shahidi, 2005). Their value in livestock diets has not been well documented (Fernandez-Duenas, 2009), but recent evident in broilers (Tavarez et al., 2011) suggests the presence of an antioxidant in feed prevents lipids from further oxidizing, resulting in improved broiler performance relative to feed not containing an antioxidant. Several antioxidants (BHA, BHT, and TBHQ) are approved for addition to products for human consumption (alone or in combination) to a limit of 200 ppm (21 CFR). Similarly, ethoxyquin is approved for addition to livestock and pet food up to a level of 150 ppm, with a maximum allowable residue of 0.5 ppm in or on the uncooked muscle meat of animals (21 CFR).

Impact of Lipid Quality on Animal Physiology and Performance

At the level of the small intestine, feeding an oxidized fat source to growing pigs has been shown to increase markers of oxidative stress (Ringseis et al., 2007) and increase triacylglycerol oxidation in blood (Suomela et al., 2005), while in young chickens it has been observed to decrease small intestinal villus length (Dibner et al., 1996a,b). In addition, studies conducted in broiler chickens (Takahashi and Akiba, 1999) found that feeding oxidized fat decreased ex vivo primary antibody production to a bacterial pathogen. Consumption of specific hydroxylated aldehydes has also been shown to have physiological effects whereby consumption of fat sources containing 4-HNE or treating cells with 4-HNE has been shown to conjugate glutathione (Uchida, 2003), increase the activation of stress pathways (Biasi et al., 2006; Yun et al., 2009), increase the expression of the inflammatory mediators in macrophages (Kumagai et al., 2004), decrease the ability of IgA to bind bacterial antigens (Kimura et al., 2006), and block macrophage signaling mechanisms (Kim et al., 2009).

Although the data cited above suggest that oxidized fat has negative effects on intestinal function, it seems that livestock are relatively resilient to low levels of lipid oxidation. Because various animal and vegetable protein meals (i.e., fish meal, meat and bone meal, and DDGS) are heat processed and may contain up to 15% lipid, the lipids in these products may be susceptible to oxidation. However, important considerations are the inclusion level of the feedstuff, the lipid concentration and composition within the feedstuff, and the temperature to which the product is processed. To date, little information is available on the level of lipid oxidation in various lipid products or in protein feedstuffs, or the potential consequences of oxidized lipids on nutritive value and livestock productivity. In broilers, only moisture, insolubles, unsaponifiables, and free fatty acids were correlated with bird performance, whereas AOM stability and PV were not (Pesti et al., 2002). Growing pigs fed 10% meat meal containing 17% lipid with a PV of 210 mEq/kg (3.6 mEq/kg of diet) (Carpenter et al., 1966) or grower pigs fed 10% meal containing 16% lipids with a PV of 214 mEq/kg (3.4 mEq/kg of diet) (L'Estrange et al., 1967) had the same performance as pigs fed a diet containing unoxidized lipids. In contrast, feeding nursery pigs 6% choice white grease with a PV of 105 mEq/kg (6.3 mEq/kg of diet) decreased daily feed intake and weight gain (DeRouchey et al., 2004).

Although an increase in the content of oxidized fat and the associated oxidative products seems to have an effect on blood lipid oxidation and intestinal barrier function and inflammatory status, the lipid oxidation indexes correlated to these effects remains largely unknown. In addition, the correlation of lipid oxidation indexes with nutrient utilization, productivity, and carcass composition and quality in swine is unknown.

LIPID ANALYSIS

Accurate determination of the lipid content in feedstuffs is important for legal (nutritional labeling), economic (product trading), health (energy intake), and quality control (food processing) reasons. In addition, determination of the lipid content of intestinal contents or feces is also important relative to understanding lipid digestion and energetics within the animal. Lipid analysis is difficult (Hammond, 2001), such that to date, the most common methods for the analysis of fats include semicontinuous extraction (Soxhlet), continuous solvent extraction (Goldfisch), and the Randal submersion method. However, with advances in technology, methods such as accelerated solvent extraction, filter bag technique, supercritical fluid extraction, summation of fatty acids by liquid chromatography, nuclear magnetic resonance, and near-infrared spectroscopy have also emerged as rapid, precise, and accurate methods for lipid analysis. Regardless of the method utilized, sample dryness, particle size, solvent type (ethers, hexanes, chloroform), extraction time, extraction temperature, pressure, and equipment calibration are all factors that affect the quantity of lipid extracted from a material and the variation noted between different analytical laboratories (Matthaus and Bruhl, 2001; Palmquist and Jenkins, 2003; Thiex et al., 2003a,b; Luthria, 2004; Thiex, 2009; Liu, 2010).

Typical extraction methods do not completely extract fatty acids (i.e., acylglycerols) or the previously described lipid-type compounds, especially if they are present as salts of divalent cations or linked to various carbohydrates or proteins. In the acid-hydrolyzed fat procedure, hydrochloric acid breaks fatty acids from the triglycerides, glycol- and phospholipids, and sterol esters, as well as disrupting lipid-carbohydrate bonds, lipid-protein bonds, and cell walls, making "lipids" available for a more complete extraction (Palmquist and Jenkins, 2003). Consequently, acid-hydrolyzed fat concentrations are higher than corresponding crude fat concentrations, although this can vary widely between ingredients (Jongbloed and Smits, 1994; Palmquist and Jenkins, 2003; Karr-Lilienthal et al., 2005; Moller, 2010). However, modifications in some of the analytical techniques may be effective in reducing this methodological difference (Schafer, 1998; Toschi et al., 2003). Because there are differences between crude fat and acid-hydrolyzed fat in feedstuffs, and because of the potential presence of cation-bound lipids in ileal contents, the use of a common analytical procedure for lipid analysis in the diet and digesta is necessary for an unbiased understanding of lipid digestion.

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4

Carbohydrates

INTRODUCTION

Swine do not have a specific dietary requirement for carbohydrates, but most of the energy that is present in diets fed to pigs originates from carbohydrates of plant origin. The primary classification of carbohydrates is based on their chemical properties (i.e., degree of polymerization, type of linkages, and characteristics of the individual monomers; Cummings and Stephen, 2007). Carbohydrates in feed consist of monosaccharides that are linked together via glycosidic bonds to form disaccharides, oligosaccharides, or polysaccharides (Figure 4-1). The glycosidic bonds that connect monosaccharides are either α-glycosidic bonds or β-glycosidic bonds depending on the positions of the carbon atoms in the monosaccharides that they connect. As an example, if an α-glycosidic bond connects carbon 1 on one monosaccharide to carbon 4 on another monosaccharide, it is referred to as an α-(1-4) glycosidic bond.

Of all the carbohydrates, only monosaccharides can be absorbed from the intestinal tract of pigs, and absorption takes place only in the small intestine. As a consequence, the pig's digestive enzymes have to digest the glycosidic bonds in carbohydrates to liberate the monosaccharides while they are in the small intestine. However, the carbohydrate-digesting enzymes secreted by pigs are capable of digesting only a limited number of glycosidic bonds, and many carbohydrates, therefore, escape enzymatic digestion in the small intestine. These carbohydrates may be fermented by intestinal microbes either in the small or large intestine, resulting in the production and absorption of short-chain fatty acids. Dietary carbohydrates may, therefore, result in absorption of either monosaccharides in the small intestine or short-chain fatty acids in the small or large intestine. Both of these groups of end products contribute to the energy status of the pig. However, carbohydrates that escape both enzymatic digestion and microbial fermentation are excreted in the feces and do not contribute to the energy status of the pig.

MONOSACCHARIDES

There are > 20 different monosaccharides in nature, but < 10 are usually present in feed ingredients included in diets fed to pigs. Monosaccharides may be classified according to the number of carbons they contain; monosaccharides that contain five carbons are called pentoses and monosaccharides that contain six carbons are called hexoses. Arabinose, ribose, and xylose are examples of pentoses, and glucose, fructose, and galactose are examples of hexoses. Glucose is by far the most abundant monosaccharide present in feed ingredients fed to pigs, but significant quantities of fructose, galactose, arabinose, xylose, and mannose may also be present, depending on the ingredient composition of the diet. Glucose and galactose may be absorbed from the small intestine via passive absorption or via an energy-dependent transporter (Englyst and Hudson, 2000; Yen, 2011), whereas fructose, arabinose, xylose, and mannose are absorbed from the small intestine only via passive absorption (Englyst and Hudson, 2000; IOM, 2001). Limited quantities of free monosaccharides are present in feed ingredients, and almost all monosaccharides in diets fed to pigs are bound together to form disaccharides, oligosaccharides, or polysaccharides.

DISACCHARIDES

Disaccharides consist of two monosaccharides linked together via glycosidic bonds. The two major disaccharides present in diets fed to pigs are sucrose and lactose (Figure 4-1). Sucrose is present in many feed ingredients of plant origin. Lactose is present only in milk, and lactose is, therefore, included in diets fed to pigs only if the diet contains milk products such as skim milk powder, whey powder, whey permeate, liquid whey, or purified lactose. Small quantities of the disaccharide maltose may also be present in some feed ingredients, and maltose is also generated as an intermediate in starch digestion. Sucrose consists

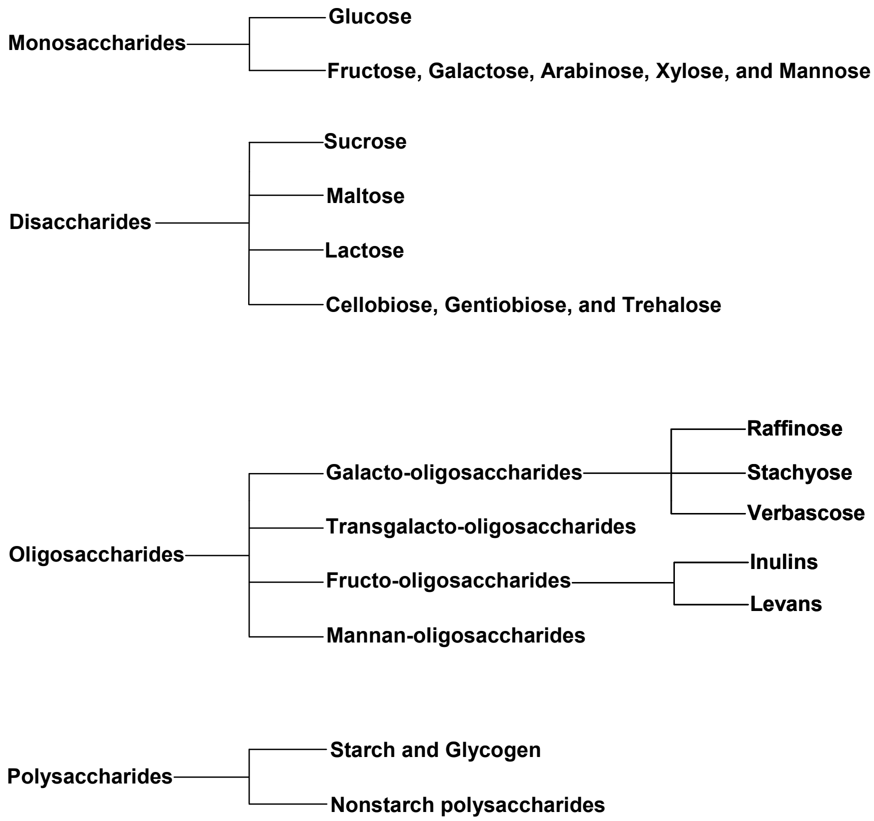

FIGURE 4-1 Carbohydrates in feed.

of glucose and fructose units that are linked together by an α-(1-2) glycosidic bond, maltose consists of two glucose units that are linked together by an α-(1-4) glycosidic bond, and lactose consists of glucose and galactose that are linked together by a β-(1-4) glycosidic bond. The glycosidic bonds in sucrose, maltose, and lactose may be digested by the enzymes sucrase, maltase, and lactase, respectively. Sucrase is expressed as part of the sucrase-isomaltase complex, which also contains the majority of the maltase activity in the small intestine (Treem, 1995; Van Beers et al., 1995). However, maltase is also expressed as part of the maltase-glucoamylase complex, whereas lactase is expressed only by the lactase gene (Van Beers et al., 1995). Sucrase, maltase, and lactase are, therefore, present in relatively large quantities in the brush border of the small intestine (Fan et al., 2001). Thus, sucrose, maltose, and lactose are easily digested with the subsequent absorption of the liberated monosaccharides. The glucose absorbed from these disaccharides is rapidly reflected in an increase in blood glucose concentration, and disaccharides are, therefore, called glycemic carbohydrates (Englyst and Englyst, 2005).

In addition to sucrose, maltose, and lactose, other disaccharides such as cellobiose, gentiobiose, and trehalose are also present in nature. Each of these disaccharides consists of two glucose units linked together via a β-(1-4) glycosidic bond (cellobiose), a β-(1-6) glycosidic bond (gentiobiose), or a β-(1-1) glycosidic bond (trehalose). Pigs do not secrete enzymes capable of digesting cellobiose or gentiobiose, and these disaccharides can, therefore, only be utilized after fermentation. There may be some cellobiose present in diets fed to pigs, but there is usually no gentiobiose. Trehalose is a storage disaccharide in insects and fungi including yeast, and may be present in diets fed to pigs if yeast or yeast products are added to the diet. Trehalose is digested by the enzyme trehalase, which is expressed in the brush border of the small intestine in pigs (Van Beers et al., 1995).

OLIGOSACCHARIDES

Oligosaccharides are compounds consisting of a few monosaccharide residues with a defined structure. The monosaccharides are joined by glycosidic bonds that cannot be digested by enzymes secreted by the glands in the small intestine of pigs. Thus, these oligosaccharides belong to the group of carbohydrates that are referred to as dietary fiber and they are subject to fermentation by microbes in either the small or large intestine with the subsequent absorption of short-chain fatty acids. Dietary fiber also consists of nonstarch polysaccharides, but oligosaccharides are separated from polysaccharides on the basis of their solubility in 80%

v/v ethanol (Englyst and Englyst, 2005). The terms "indigestible oligosaccharides," "resistant oligosaccharides," and "resistant short-chain carbohydrates" are synonymous and refer to any carbohydrate that resists pancreatic and small intestinal digestion and is soluble in 80% ethanol (Englyst et al., 2007). This analytical definition of oligosaccharides includes galacto-oligosaccharides (including transgalacto-oligosaccharides), fructo-oligosaccharides, and mannan-oligosaccharides.

Galacto-oligosaccharides

The largest group of galacto-oligosaccharides (also referred to as α-galactosides) consists of the oligosaccharides present in legumes, including raffinose, stachyose, and verbascose (Cummings and Stephen, 2007; Martinez-Villaluenga et al., 2008). Raffinose is a trisaccharide composed of a unit of galactose linked to sucrose via an α-(1-6) glycosidic bond. Stachyose is composed of two galactose units linked to sucrose via an α-(1-6) bond, and verbascose is composed of three galactose units linked to sucrose via an α-(1-6) bond (Cummings and Stephen, 2007). Galacto-oligosaccharides are primarily present in legume seeds such as peas and beans (Cummings and Stephen, 2007). The glycosidic bonds that connect the monosaccharides in galacto-oligosaccharides can be digested by the enzyme α-galactosidase. However, like many other animals, pigs do not secrete α-galactosidase in the small intestine, which is the reason galacto-oligosaccharides are not enzymatically digested in the small intestine. They are, however, readily fermented by intestinal microbes with the majority of the fermentation taking place in the small intestine (Bengala Freire et al., 1991; Smiricky et al., 2002). However, some of the galacto-oligosaccharides escape fermentation in the small intestine and enter the large intestine where they may exert a prebiotic effect (Meyer, 2004). Addition of α-galactosidase and other carbohydrases to diets fed to pigs may improve small intestinal digestibility of oligosaccharides (Kim et al., 2003), but that does not always improve pig growth performance (Jones et al., 2010). Some plants, such as barley, express α-galactosidase, which is involved not only in the metabolism of raffinose, but also with leaf development and stress tolerance (Chrost et al., 2007).

A second group of galacto-oligosaccharides is referred to as transgalacto-oligosaccharides. They are not synthesized in nature, but consist of oligosaccharides that are commercially produced by transglycosylation using lactose as the substrate (Houdijk et al., 1999; Meyer, 2004). Reactions catalyzed by β-galactosidase convert lactose to β-(1-6)-linked galactose units connected to a terminal glucose unit via an α-(1-4) linkage. Degree of polymerization can vary from two to five (Meyer, 2004). Transgalacto-oligosaccharides are believed to act as prebiotics, and they may contribute to improved intestinal health of young pigs, although conclusive evidence for this effect has yet to be presented.

Fructo-oligosaccharides

Fructo-oligosaccharides or fructans are carbohydrates that are composed mainly of fructose monosaccharides with varying degree of polymerization (BeMiller, 2007). Fructo-oligosaccharides are classified as inulins or levans.

Inulins are storage carbohydrates that are present in several fruits and vegetables including onions, Jerusalem artichokes, wheat, and chicory (Englyst et al., 2007). The chain length of inulins varies from 2 to 60, with an average degree of polymerization of 12 (Roberfroid, 2005). Commercial hydrolysis of inulin from chicory produces inulin-type fructans, which are linear polymers mainly composed of β-(2-1)-linked fructose units that are often terminated with sucrose at the reducing end (BeMiller, 2007). A glucose molecule and side chains having β-(2-6) linkages may also be present in some inulin-type fructans (Meyer, 2004; Roberfroid, 2005).

Levans are β-(2-6)-linked fructans synthesized by some bacteria and fungi that secrete levansucrase (Franck, 2006). Levansucrase catalyzes transglycosylation reactions that convert sucrose to levans that may contain β-(2-1)-linked side chains (BeMiller, 2007). Fructans with a high degree of polymerization (> 10^7 Da) are mainly the levan type (Franck, 2006), but they are not commercially produced (Meyer, 2004). Aside from being a source of dietary fiber, fructans are prebiotics and they may promote the growth of *Bifidobacteria* spp. (Franck, 2006) and *Lactobacillus* spp. (Mul and Perry, 1994) and reduce the growth of harmful bacteria such as *Clostridia* spp. (Franck, 2006), thus contributing to improved intestinal health.

Mannan-oligosaccharides

Mannan-oligosaccharides are polymers of mannose. Most of the mannan-oligosaccharides used in diets fed to swine are derived from yeast cell walls (Zentek et al., 2002). Yeast cell wall is composed of a network of mannans, β-glucans, and chitin (Cid et al., 1995). The mannose units are located in the outer surface of the cell wall and are attached to the inner β-glucan component of the cell wall through β-(1-6) and β-(1-3) glycosidic linkages (Cid et al., 1995). Mannan-oligosaccharides are not digestible by gastric and intestinal enzymes (Zentek et al., 2002) and when fed to animals, mannan-oligosaccharides may function as prebiotics and as immune modulators. Mannan-oligosaccharides may also aid in gastrointestinal pathogenic resistance by acting as alternative receptors for bacteria (i.e., *Escherichia coli*) that have a mannan-specific lectin (Mul and Perry, 1994; Swanson et al., 2002).

POLYSACCHARIDES

Polysaccharides are divided into two groups: Starch and glycogen and nonstarch polysaccharides. In practical diets fed to pigs, both of these groups of carbohydrates are present in relatively large quantities.

Starch and Glycogen

Starch

Starch is the principal carbohydrate in most diets because it is the major storage carbohydrate of cereal grains. Starch is composed entirely of glucose units and is unique among carbohydrates because it occurs in nature as granules that are stored in amylose and amylopectin polymers (BeMiller, 2007). Most cereal starches contain about 25% amylose and 75% amylopectin. Amylose (Figure 4-2) is predominantly a linear chain of glucose residues linked by α-(1-4) glycosidic bonds, although a few α-(1-6) bonds may occur as side chains (Cummings and Stephen, 2007). Amylopectin (Figure 4-3) is a large, highly branched polymer composed of both α-(1-4) and α-(1-6) glycosidic linkages (Cummings and Stephen, 2007). Starch that is composed entirely or almost entirely of amylopectin is referred to as waxy starch (BeMiller, 2007).

Digestion of starch is initiated when the feed is mixed with salivary amylase secreted in the mouth (Englyst and Hudson, 2000). This digestion process is short because salivary amylase is deactivated by the low pH in the stomach as the feed is swallowed (Englyst and Hudson, 2000). Most of the digestion of starch occurs in the small intestine, where it is hydrolyzed to maltose, maltotriose, and isomaltose (also called α-dextrins) subunits by pancreatic and intestinal α-amylase and isomaltase (Groff and Gropper, 2000). Maltase hydrolyzes maltose and maltotriose to its glucose monomers, and isomaltase (also called α-dextrinase) hydrolyzes the α-(1-6) glycosidic linkage of isomaltose to produce glucose molecules (Groff and Gropper, 2000) that are easily absorbed from the small intestine via active or passive transport. Although enzymes can completely digest starch, the rate and extent of starch digestion in the small intestine varies depending on several factors including (1) the nature of the crystallinity of the starch granule or the source of starch, (2) the amylose:amylopectin ratio, and (3) the type and extent of processing of the starch (Cummings et al., 1997; Englyst and Hudson, 2000; Svihus et al., 2005). Because of the different factors that affect starch digestibility, starch can be classified further, based on the rate of its digestion and the appearance of glucose in blood, as either rapidly available starch or slowly available starch (Englyst et al., 2007). Nevertheless, starch digestion is an efficient process and for most cereals grains, starch digestion in the small intestine is > 95% (Bach Knudsen, 2001), whereas the ileal digestibility of starch in field peas is approximately 90% (Canibe and Bach Knudsen, 1997; Sun et al., 2006; Stein and Bohlke, 2007). Starch digestibility in peas is less than in cereal grains because some of the starch in peas is entrapped in fibrous cell-wall components and, therefore, not accessible to digestive enzymes (Bach Knudsen, 2001). There is also a greater amylose:amylopectin ratio in peas than in cereal grains, which also may reduce the digestibility of starch (Bach Knudsen, 2001).

Starch that is not digested in the small intestine is referred to as resistant starch (Brown, 2004). Resistant starch is naturally present in all starch-containing feeds, but the amount of resistant starch depends on the source of the starch, the processing techniques used in the preparation of the feed, and the storage conditions of the starch before consumption (Livesey, 1990; Brown, 2004; Goldring, 2004).

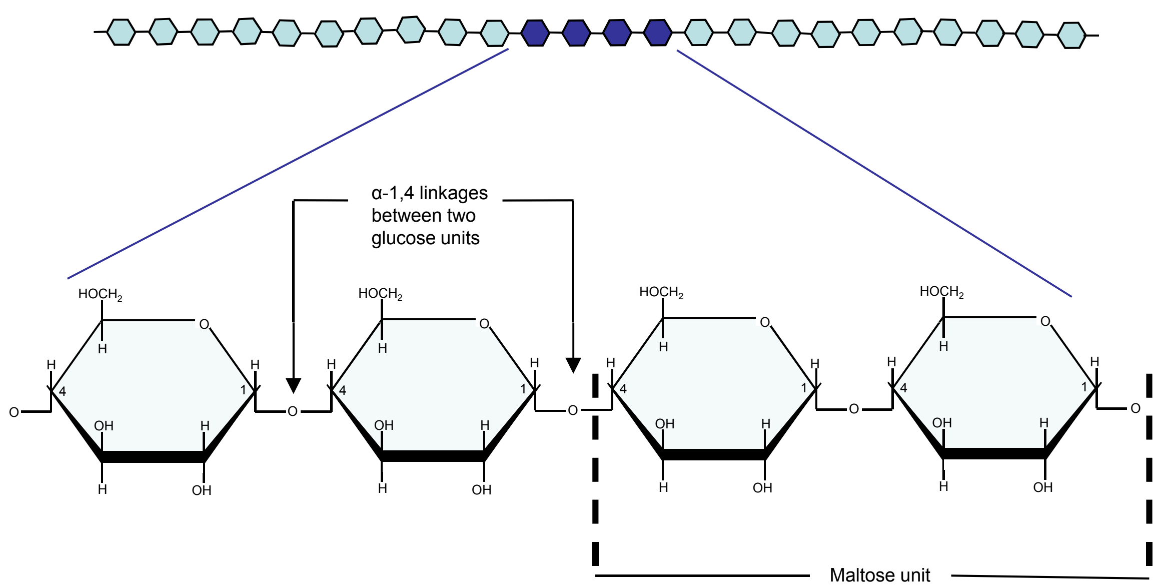

FIGURE 4-2 Structure of amylose.

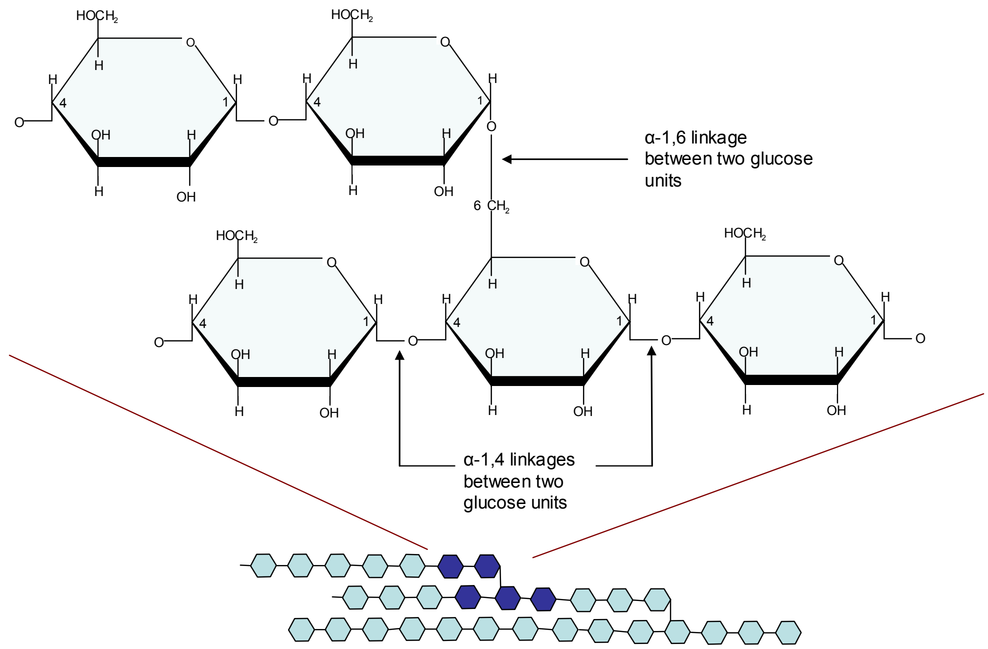

FIGURE 4-3 Structure of amylopectin.

Resistant starch has four classifications. Resistant starch 1 refers to starches that are physically inaccessible to digestive enzymes because they are enclosed in an indigestible matrix (BeMiller, 2007). Whole or partly milled grains contain resistant starch that belongs to this class (Brown, 2004). Resistant starch 2 refers to native (uncooked) starch granules that resist digestion because of the granules' conformation or structure (Brown, 2004). Processing of this type of starch can make the starch susceptible to enzymatic hydrolysis. However, high-amylose starch is unique because its granules are not affected by processing and it retains its ability to resist hydrolysis by digestive enzymes (Brown, 2004). Resistant starch 3 refers to retrograded starches, which are starches that have been gelatinized and cooled to allow crystalline formation that resists digestion (Brown, 2004). Resistant starch 4 refers to starch that has been modified by certain chemical reactions to reduce its enzymatic susceptibility to digestive enzymes (Brown, 2004). Resistant starch is readily fermented in the large intestine with the subsequent absorption of short-chain fatty acids and very little starch is excreted in the feces.

Glycogen

Animals store glucose in muscles and liver in the form of glycogen, which in structure is similar to amylopectin and consists of branched chains of glucose units that are connected via α-(1-4) and α-(1-6) glycosidic bonds. Glycogen is digested in the same way and by the same enzymes as amylopectin, and digestion of glycogen results in absorption of glucose from the small intestine. Animals usually store relatively small amounts of glycogen in the body because most energy is stored as lipid (primarily triacylglycerols). Pigs, therefore, consume glycogen only if they are fed diets containing meat meal or other animal products containing glycogen. In most commercial diets fed to pigs, little or no glycogen is present.

Nonstarch Polysaccharides

Nonstarch polysaccharides belong to the group of carbohydrates that are referred to as dietary fiber, which is defined as carbohydrates that are not digested or are poorly digested by enzymes in the small intestine, but are completely or partially fermented by microbes (De Vries, 2004). The concept of small intestinal indigestibility is also shared by the terms "unavailable carbohydrates" and "nonglycemic carbohydrates" (Englyst et al., 2007). Nonstarch polysaccharides differ from disaccharides and starch and glycogen in that the component monosaccharides are not connected by α-(1-4) glycosidic bonds or other bonds that may be digested by small intestinal enzymes (Englyst et al., 2007). Thus, inclusion of nonstarch polysaccharides in diets fed to pigs will not result in absorption of monosaccharides from the small intestine, but short-chain fatty acids may be absorbed from the small or large intestine as a result of fermentation. Nonstarch polysaccharides are divided into cell wall components and non-cell wall components.

Cell Wall Components

Cellulose and hemicelluloses are the most common nonstarch polysaccharides in cell walls, but arabinoxylans, xyloglucans, arabinogalactans, galactans, and mixed β-glucans may also be present (Bach Knudsen, 2011). Cellulose is a linear, unbranched chain of glucose units with β-(1-4) linkages, which enable the chains to pack closely and form microfibrils that provide structural integrity to the plant cells and tissues (Cummings and Stephen, 2007; Englyst et al., 2007). Because of the nature of the glycosidic linkages, cellulose is not digested by small intestine enzymes secreted by pigs, but it may be fermented by microbes in the small or large intestine.

Hemicellulose differs from cellulose in that it is a branched-chain polysaccharide composed of different types of hexoses and pentoses (Cummings and Stephen, 2007). The most common hemicellulose in annual plants, including cereal grains, is xylan (BeMiller, 2007), which consists of a xylose backbone that may be linear or highly branched (BeMiller, 2007). Side chains are present in the linear or branched core structure and are usually composed of arabinose, mannose, galactose, and glucose (Cummings and Stephen, 2007). Some hemicelluloses also contain uronic acids that are derived from glucose (glucuronic acid) or from galactose (galacturonic acid; Southgate and Spiller, 2001). The presence of uronic acids gives hemicelluloses the ability to form salts with metal ions such as calcium and zinc (Cummings and Stephen, 2007).

Lignin is not a carbohydrate, but it is closely associated with plant cell walls and is included in the analysis of dietary fiber (Lunn and Buttriss, 2007). Lignin is formed by cross-linkage of phenyl propane polymers of coumaryl, guaiacyl, coniferyl, and sinapyl alcohols (Kritchevsky, 1988). As the plant matures, lignin penetrates the plant polysaccharide matrix and forms a three-dimensional structure within the matrix of the cell wall (Southgate, 2001). Lignin is resistant to enzymatic and bacterial degradation. As a consequence, plants with a high concentration of lignin are poorly digested (Southgate, 2001; Wenk, 2001).

Non-Cell Wall Components

Carbohydrates that are not components of the plant cell wall but are considered nonstarch polysaccharides include pectins, gums, and resistant starches. Commercially available pectin is usually extracted from citrus peel or apple pomace, although other sources of pectin are also available (Fernandez, 2001). A key feature of pectins is that they are composed primarily of linear polymers of galacturonic acids that are linked together by α-(1-4) linkages (BeMiller, 2007). Pectins may also contain side chains of rhamnose, galactose, and arabinose (Cummings and Stephen, 2007).

Gums are natural plant polysaccharides, but may also be produced by fermentation. Naturally occurring gums can be formed as exudates from plants or shrubs that are physically damaged or they can be a part of the seed endosperm (BeMiller, 2007). An example of an exudate gum is gum arabic and an example of a gum from seed endosperm is guar gum. Xanthan gum and pullulan are examples of gums produced via fermentation.

Gum arabic (or acacia gum) is a heterogeneous material that consists mainly of a branched β-(1-3)-linked galactose backbone with ramified side chains composed of arabinose, rhamnose, galactose, and glucuronic acid linked through the 1-6 positions (Osman et al., 1995; Williams and Phillips, 2001). Guar gum is a galactomannan that consists of a linear β-(1-4) mannose backbone, with some of the mannose units having a single galactose unit as a side chain (BeMiller, 2007).

ANALYSES FOR CARBOHYDRATES

Carbohydrates in feed ingredients (Figure 4-4) may be analyzed using different procedures and each procedure provides specific components of carbohydrates. Concentrations of monosaccharides are usually quantified using enzymatic or high-performance liquid chromatography (HPLC) procedures (McCleary et al., 2006). Concentrations of disaccharides, oligosaccharides, and starch are usually analyzed using enzymatic-gravimetric procedures. There are, however, several different procedures available for the analysis of the nonstarch polysaccharides. The oldest procedure is the Wende procedure in which carbohydrates are separated into nitrogen-free extract and crude fiber. The concentration of crude fiber is determined gravimetrically after acid digestion and includes most of the lignin, various amounts of cellulose, and smaller amounts of hemicellulose (Grieshop et al., 2001; Mertens, 2003). Because of the lack of consistency in the recovery of cellulose and hemicellulose among feed ingredients, the analyzed concentration of crude fiber does not adequately describe the nutritional value of a feed ingredient and this procedure is, therefore, rarely used to characterize feed ingredients fed to pigs.

The detergent fiber procedure is a chemical-gravimetric procedure that divides nonstarch polysaccharides into neutral detergent fiber (NDF), acid detergent fiber (ADF), and lignin (Robertson and Horvath, 2001). The concentration of cellulose is calculated as the difference between the concentration of lignin and ADF, and the concentration of hemicellulose is calculated as the difference between ADF and NDF. Although the detergent procedure is widely used, it does not always provide an accurate estimate of fiber components in feed ingredients because the soluble dietary fibers, such as pectins, gums, and β-glucans, are not recovered in this analysis (Grieshop et al., 2001). Thus, the greater the concentration of soluble fiber, the less accurate are the results obtained with the detergent fiber procedure in terms of quantifying the total fiber components of a feed ingredient.

Some of the limitations of the detergent procedures are

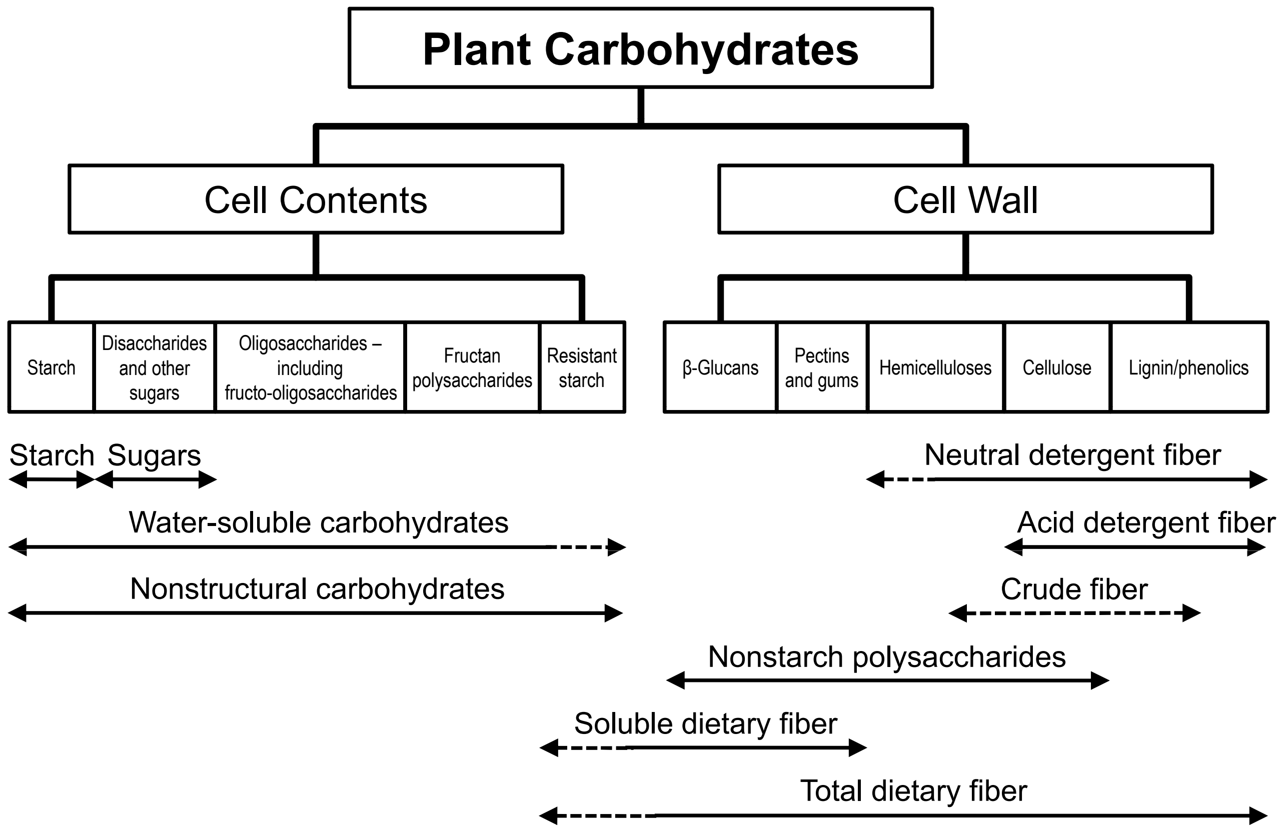

FIGURE 4-4 Categories of dietary carbohydrates based on current analytical methods.

overcome by analysis for total dietary fiber (TDF). This procedure may quantify all the fiber fractions in a feed ingredient and also divide the fibers into soluble and nonsoluble dietary fiber (AOAC, 2007). Results obtained with the TDF procedure more closely represent the total dietary fiber fraction in a feed ingredient than results obtained with the detergent procedure (Mertens, 2003). The major challenge with the TDF procedure is that results obtained are less reproducible than results obtained with the detergent procedure and the TDF procedure is, therefore, not universally implemented in nutrition laboratories.

The nonstarch polysaccharides in a feed ingredient may also be quantified using enzymatic-chemical methods and there are two such procedures that are commonly used: the Uppsala procedure and the Englyst procedure. The Uppsala procedure quantifies the nonstarch polysaccharide fraction as the sum of amylase-resistant polysaccharides, uronic acid, and lignin (AOAC, 2007). The residue is then divided into soluble and insoluble fractions using 80% ethanol, and neutral sugars and uronic acids are subsequently quantified (Theander and Aman, 1979). The Englyst procedure for determining nonstarch polysaccharides differs from the Uppsala procedure by excluding lignin and resistant starch from the final value (Englyst et al., 1996; Grieshop et al., 2001).

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5

Water

INTRODUCTION

Although water is universally recognized as an important nutrient, there has been surprisingly little research conducted on water requirements of swine. In the future, more research may be needed into the physiologic/metabolic needs of swine because of limitations in water supply (Deutsch et al., 2010) for the production of swine as well as issues related to waste removal and application in many geographic areas.

FUNCTIONS OF WATER

Water fulfills a number of physiological functions necessary for life (Roubicek, 1969). It is a major structural compound giving form to the body through cell turgidity, and it plays a crucial role in temperature regulation. The high specific heat of water makes it ideal for dispersing the surplus heat produced during various metabolic processes. About 580 calories of heat are released when 1 g of water changes from liquid to vapor (Thulin and Brumm, 1991). Water is important in the movement of nutrients to the cells of body tissues and for the removal of waste products from these cells. The high dielectric constant of water gives it the ability to dissolve a wide variety of substances and transport them throughout the body via the circulatory system. In addition, water plays a role in virtually every chemical reaction that takes place in the body. The oxidation of carbohydrates, fats, and proteins all result in the formation of water. The metabolism of these compounds to yield their energy is achieved through a series of complex reactions that ultimately end with carbon dioxide and water in addition to the energy. Finally, water is important in the lubrication of joints (i.e., synovial fluid) and in providing protective cushioning for the nervous system (i.e., cerebrospinal fluid).

The water content of a pig varies with its age. Water accounts for as much as 82% of the empty body weight (whole body weight less gastrointestinal tract contents) in a 1.5-kg neonatal pig and declines to as little as 48-53% in a 110-kg market pig, depending on the lean content of the market pig (Shields et al., 1983; de Lange et al., 2001). This change with age is principally because the fat content of the pig increases with age and adipose tissue is considerably lower in water content than is muscle (Georgievskii, 1982).

WATER TURNOVER

Swine obtain water from three sources: (1) water that is consumed directly; (2) water that is a component of feedstuffs (typically about 10-12% of air-dry feed); and (3) water that originates from the breakdown of carbohydrate, fat, and protein (metabolic water). The oxidation of 1 kg of fat, carbohydrate, or protein produces 1,190, 560, or 450 g of water, respectively (NRC, 1981). According to Yang et al. (1984), every 1 kg of air-dry feed consumed will produce between 0.38 and 0.48 kg (or L) of metabolic water.

Water is lost from the body by four routes: (1) the lungs (respiration), (2) the skin (evaporation), (3) the intestines (defecation), and (4) the kidneys (urination). Moisture is continually lost from the respiratory tract during the normal process of breathing. Incoming air is both warmed and moistened as it passes over the lining of the respiratory tract and is expired at approximately 90% saturation (Roubicek, 1969). For pigs in a thermoneutral environment, respiratory water loss has been estimated to be 0.29 and 0.58 L/day for pigs of 20 and 60 kg body weight, respectively (Holmes and Mount, 1967). The extent of loss is affected by both temperature and relative humidity; water loss increases with increased temperature and decreases with increased humidity.

Sweating and insensible water losses from the skin are not major sources of water loss in swine because the sweat glands are largely dormant. Within the thermoneutral zone, the rate of moisture loss has been estimated to be between 12 and 16 g/m^2 (Morrison et al., 1967). Increasing the environmental temperature from –5 to 30°C increased water loss from 7 to 32 g/m^2 (Ingram, 1964). However, increased relative humidity had no effect on this loss (Morrison et al., 1967).

Significant quantities of water are lost in the feces. The amount of feces a pig produces per day in confinement ranges from 8 to 9% of its body weight, with a water content varying from 62 to 79% (Brooks and Carpenter, 1993). Water loss through the gut will vary with the nature of the diet. In general, the greater the proportion of undigested material, the greater the water loss (Maynard et al., 1979). Water loss increases with increased fiber intake (Cooper and Tyler, 1959) and with intake of feeds that have laxative properties (Sohn et al., 1992; Darroch et al., 2008). Water loss via the feces is also increased during diarrhea (Thulin and Brumm, 1991).

Urination is the major route of water excretion in swine, although the amount of water excreted in the urine is highly variable. The kidneys regulate the volume and composition of body fluids by excreting more or less water, depending on water intake and excretion through other mechanisms. In general, water excretion is thought to increase when pigs are fed diets that contain greater amounts of minerals and protein. Wahlstrom et al. (1970) demonstrated that the greater the concentration of protein in the diet, the greater the water loss, and thus the greater the water requirement. Similarly, Sinclair (1939) demonstrated that increased intake of salt results in increased water intake and a concomitant increase in urinary excretion. However, in a commercial enterprise, Shaw et al. (2006) did not observe significant effects of relatively large differences in dietary protein or mineral concentration on water usage, leading them to conclude that factors other than dietary protein and mineral concentration and daily protein and mineral intake (such as equipment design or behavioral differences among pigs) may have a relatively large effect on water usage. Consequently, dietary strategies to regulate water usage may have a limited effect if other important factors are ignored.

WATER REQUIREMENTS

Many factors, including dietary, physiological, and environmental, affect the water requirements of swine (NRC, 1981; Mroz et al., 1995). Because the amount of water in a pig's body at any given age is relatively constant, pigs have to consume sufficient water on a daily basis to balance the amount of water lost. Any factor known to increase water excretion will, therefore, increase water requirements. The minimum requirement for water is the amount needed to balance water losses, produce milk, and form new tissue during growth or pregnancy.

In determining water requirements, it is important to distinguish between requirements/consumption and usage (Fraser et al., 1993). True water requirements of pigs are usually overestimated because wastage is generally not considered. Based on water turnover rates measured using tritiated water, water requirements of pigs under confinement and normal dry feeding conditions were estimated to be approximately 120 and 80 mL/kg of body weight for growing (30-40 kg) and nonlactating adult pigs (157 kg), respectively (Yang et al., 1981).

However, because of the difficulty in making these types of measurements, water usage is typically used to estimate water requirement. Many factors other than metabolic need of the pig influence total water usage in swine production and these include ambient temperature as it affects intentional water wastage by pigs or dripping/misting systems specifically employed to cool pigs. Equipment selection and placement as well as the number of drinkers and water flow rate are management or physical-facility-related items that may affect water usage. Information about the effects of these types of factors on water usage was reviewed by Brumm (2010).

Suckling Pigs

A common assumption is that suckling pigs do not drink water and can completely satisfy their water requirements by drinking milk, because milk contains approximately 80% water (Pond and Houpt, 1978). However, suckling pigs do, in fact, drink water within 1 or 2 days of birth (Aumaitre, 1964). In addition, because milk is a high-protein, high-mineral food, its consumption can cause increased urinary excretion, which might actually lead to a water deficit (Lloyd et al., 1978).

Fraser et al. (1988) measured water use by 51 suckling litters during the first 4 days after farrowing. The use varied greatly among litters, ranging from 0 to 200 mL/pig per day, with an average daily consumption per pig of 46 mL. This intake is considerably greater than that reported in earlier work, in which average daily water intake per pig was closer to 10 mL. Fraser et al. (1993) speculated that the increased consumption recorded in more recent studies may reflect an increased emphasis on temperature control in farrowing rooms and that the higher temperatures currently used may lead to an increase in moisture loss from the pig. Their data showed almost a fourfold increase in water consumption when suckling pigs were housed in rooms at 28°C than when housed at 20°C.

Fraser et al. (1988) suggested that providing a supplemental water supply may help to reduce preweaning mortality. They suggested that undernourished pigs, especially those housed in warm environments, may be prone to dehydration during the first few days after farrowing and that at least some pigs have the developmental maturity to compensate by drinking water. Exposed water surfaces (e.g., bowls or cups) are better than nipple drinkers for this purpose (Phillips and Fraser, 1990, 1991).

After the first week of life, the principal concern regarding the water consumption of suckling pigs is the role it plays in stimulating creep feed consumption. Although the consumption of creep feed by pigs is usually low during the first 3 weeks, subsequent feed intake is less if water is not provided

(Friend and Cunningham, 1966). Pig health is a factor that affects water intake. Pigs with diarrhea consumed 15% less water than healthy pigs (Baranyiova and Holub, 1993).

Weanling Pigs

Gill et al. (1986) measured the water intake of weaned pigs from 3 to 6 weeks of age. Daily water intake during the first, second, and third week after weaning averaged 0.49, 0.89, and 1.46 L per pig. The relationship between feed intake and water consumption was described by Brooks et al. (1984) using the following equation:

$$\text{Water intake (L/day)} = 0.149 + (3.053 \times \text{Daily dry feed intake in kg}) \quad \text{(Eq. 5-1)}$$

McLeese et al. (1992) observed two distinct patterns of water intake. During the first period, lasting about 5 days after weaning, water intake fluctuated independently of apparent physiological need and did not seem to be related to growth, feed intake, or the severity of diarrhea. In the second period, water intake followed a consistent pattern that paralleled growth and feed intake. The authors speculated that during the first few days after weaning, water consumption might be high so that the pigs could obtain a sense of satiety in the absence of feed intake. Torrey et al. (2008) concluded that early-weaned pigs do not obtain a sense of satiety through water consumption. They also observed that although the type of drinking device for early weaned pigs could affect behavior and water wastage, it did not affect total feed intake or growth performance. An additional observation about the pattern of feed intake was reported by Brooks et al. (1984), who observed a diurnal pattern to water intake for weaned pigs housed under conditions of constant light, with greater consumption from 0830 to 1700 hours than from 0700 to 0830 hours.

Nienaber and Hahn (1984) studied the effects of water flow restriction on the performance of weanling pigs. Their results showed little effect on growth when flow rates were varied between 0.1 and 1.1 L/minute. However, water use was significantly greater with a more rapid flow rate, which was attributed to increased wastage of water. Similarly, water use increased when water nipples were tilted up (at 45 degrees) versus down (at 45 degrees) in position (Carlson and Peo, 1982). Weanling pigs in pens with water nipples placed in the down position gained 6.5% faster, were 7% more efficient in feed conversion, and used 63% less water than pigs in pens with water nipples pointing up. There was no advantage in using drip versus nondrip waterers (Ogunbameru et al., 1991).

Growing-Finishing Pigs

For growing-finishing pigs, free access to water located near feed dispensers is advisable, and such access is normally provided for dry-feeding systems. The rate (grams per hour) of digesta or water emptying from the stomach increases as the water intake increases (Low et al., 1985). This process regulates the dry matter content of the gastric digesta, particularly during the first hour after feeding.

Factors such as feed intake, ingredients contained in the diet, ambient temperature and humidity, state of health, and stress affect water requirements. Water consumption generally has a positive relationship with feed intake and body weight. The minimum requirement for pigs between 20 and 90 kg body weight is approximately 2 kg of water for each kilogram of feed. The voluntary water intake of growing pigs allowed to consume feed ad libitum is approximately 2.5 kg of water for each kilogram of feed; pigs receiving restricted amounts of feed have been reported to consume 3.7 kg of water per kilogram of feed (Cumby, 1986). The difference between pigs allowed ad libitum access to feed and restricted-fed pigs may be due to the tendency of pigs to fill themselves with water if their appetite is not satisfied by their feed allowance.

Braude et al. (1957) gave pigs unrestricted amounts of dry feed up to 3 kg/pig daily and free access to water. From 10 to 22 weeks of age, the water-to-feed ratio averaged 2.56:1. From 16 to 18 weeks of age, the maximum average daily intakes of water and feed were 7.0 and 2.7 kg/pig, respectively.

Olsson and Andersson (1985), using nose-operated drinking devices, concluded that water consumption at feeding for growing-finishing pigs has a distinct periodicity, with a peak at the beginning and end of the feeding period. Water consumption between feeding periods peaked 2 hours after the morning feeding and 1 hour after the afternoon feeding. These results support the conclusions of Yang et al. (1984) that growing pigs have a tendency, when feed intake is restricted, to increase the total water ingested, possibly because of a desire for abdominal fill. In general, their results suggest that if feed access was restricted, water for abdominal fill was consumed during the afternoon.

Barber et al. (1988) studied the effect of water delivery rate and number of drinking nipples on the water use of growing pigs. A high (900 mL/minute) delivery rate increased water use (3.8 L/day) compared with a low (300 mL/minute) delivery rate (1.9 L/day). However, pig performance was not affected. Increasing the number of nipples per pen (eight pigs per pen) from one to two had no effect on either water use or pig performance.

Mount et al. (1971) reported little difference in water consumption by growing pigs kept at temperatures of 7, 9, 12, 20, or 22°C, although there was considerable variation among pigs at any one temperature. However, at 30 and 33°C, the intake of water increased by 25-50%, depending on the specific comparison. At 30°C and above, Close et al. (1971) observed behavioral responses to increased temperature. Urine and feces were voided over the whole pen area, and water was spilled from the water bowl, presumably in an attempt to cool the pig's body surface.

The temperature of the water itself will affect intake because additional energy is required to warm liquids consumed at temperatures below that of the body. In an Australian study, pigs were reared from 45 to 90 kg body weight in either a cool room where the temperature was maintained at a constant 22°C or in a hot room where the temperature alternated from 35 to 24°C every 12 hours (Vajrabukka et al., 1981). Pigs kept in the cool room drank 3.3 L daily when the water was cooled to 11°C, compared with almost 4.0 L when the water was warmed to 30°C. In contrast, pigs kept in the hot room drank 10.5 L when the water was supplied at 11°C, but only 6.6 L when it was supplied at 30°C.

Hagsten and Perry (1976) reported reductions in water consumption and daily weight gain of 20 and 38%, respectively, when growing pigs were fed a diet containing less than 0.20%, compared to diets of 0.27% or 0.48%, total salt (NaCl) or salt equivalent.

Use of antibiotics may also affect water consumption; some researchers report an increase in consumption, whereas others have reported a decrease. It has been hypothesized that the effect of antibiotics on water demand will depend on the relative extent to which water loss is reduced by the control of diarrhea and water demand is increased to enable renal clearance of the antibiotic or its residues (Brooks and Carpenter, 1993).

In wet feeding systems, water:feed ratios ranging from 1.5:1 to 3.0:1 seemed to have little effect on the performance or carcass quality of growing-finishing swine (Barber et al., 1963; Holme and Robinson, 1965). However, pigs fed with wet feeding systems have to be given access to an additional source of fresh water to ensure adequate water intake in case of sudden changes in barn temperature or unexpected alterations in feed composition (e.g., high salt or protein concentrations).

Gestating Sows

The water intake of pregnant gilts increases in proportion to dry matter intake (Friend, 1971). For unbred gilts, feed and water intake decreased during estrus (Friend, 1973; Friend and Wolynetz, 1981). Bauer (1982) observed that unbred gilts consumed 11.5 L of water daily, whereas gilts in advanced pregnancy consumed 20 L. These quantities are similar to the values of 13.5 and 25.1 L (Riley, 1978) and 10.0 and 17.7 L (Lightfoot and Armsby, 1984) for dry and lactating sows, respectively. Urinary disorders (e.g., cystitis, infections, high urine pH, and inflammation) are common in sows, and low water intake is strongly implicated (Madec, 1984). Pregnant sows given restricted levels of feed intake may show a desire to compensate for inadequate gut fill by an enhanced water intake. Increasing the fiber content of gestation diets is likely to increase the water:feed ratio required.

Lactating Sows

Lactating sows need considerable amounts of water, not only to replace the 8-16 kg of milk secreted daily but also to void large amounts of metabolic end products (e.g., urea from catabolism of amino acids as a consequence of a different amino acid profile of milk compared to body tissue or feed) in the urine. Daily water consumption of lactating sows was shown to vary from 12 to 40 L/day, with a mean of 18 L/day (Lightfoot, 1978). Similarly, daily water consumption varied from < 11 L to > 17 L in a study by Seynaeve et al. (1996) and was influenced by salt content of the lactation diet. These quantities are similar to other recorded values for the daily water intake of lactating sows of 20 L (Bauer, 1982), 25.1 L (Riley, 1978), 17.7 L (Lightfoot and Armsby, 1984), and 17.3 L (Peng et al., 2007).

Phillips et al. (1990) observed no difference in water consumption between sows housed in crates with high (2 L/minute) versus low (0.6 L/minute) flow rates of nipple drinkers. Similarly, Peng et al. (2007) reported that the height of the nipple drinkers above the floor (600 mm vs. 300 mm) did not affect water consumption patterns. Peng et al. (2007) also observed that use of a self-fed wet/dry feed–water system in lactation, which provides sows choices of when to eat, how much to eat, and whether dry feed is mixed with water during consumption, enhanced sow feed intake, improved litter growth performance, and wasted less water than a hand-fed feed–water system.

During periods of heat stress in lactating sows, the provision of chilled drinking water (10 or 15 vs. 22°C) under farm conditions where ambient temperature was consistently above 25°C had positive effects (Jeon et al., 2006). Sows given the chilled water (both 10 and 15°C) consumed more feed (5.3 vs. 3.8 kg/day) and water (38.1 vs. 31.2 L/day), and had lower rectal temperatures and respiration rates than control sows. Weaning weights and average daily gain of litters from the sows drinking chilled water were greater than those from control sows.

Boars

There are few data on the water requirements of boars, but free access to water is advisable. Straub et al. (1976) observed water intakes in growing boars (70-110 kg) of up to 15 L/day at 25°C compared with approximately 10 L/day at 15°C.

WATER QUALITY

Elements and substances can occur in water at concentrations that are harmful to pigs (NRC, 1974). Water may contain a variety of microorganisms, including both bacteria and viruses. Of the former, *Salmonella*, *Leptospira*, and *Escherichia coli* are the most commonly encountered (Fraser et al., 1993). Water can also carry pathogenic protozoa as well as eggs or cysts of intestinal worms (Fraser et al., 1993). Whether the presence of these microorganisms will be detrimental is largely dependent on the specific types found and their concentration. The Bureau of National Affairs (1973) proposed that water used for livestock not contain more than 5,000 coliforms/100 mL. However, this recommendation can be considered as only a guide because some pathogens may be harmful below this level, whereas other, more benign, microorganisms can be tolerated at much greater concentrations. Bacterial contamination is usually more common in surface waters than in underground supplies such as deep wells and artesian water (MDH, 2011; Skipton et al., 2008).

Total dissolved solids (TDS) is a measure of the total inorganic matter dissolved in a sample of water. Calcium, magnesium, and sodium in the bicarbonate, chloride, or sulfate form are the most common salts found in water with a high TDS (Thulin and Brumm, 1991). Water containing > 6,000 ppm TDS may cause temporary diarrhea and increased daily water intake, although health and performance are not usually affected. Paterson et al. (1979) offered water containing 5,060 ppm TDS to gilts and sows from 30 days postbreeding through weaning at day 28 and reported no significant effects on reproduction. The addition of up to 6,000 ppm TDS to water offered to weaned pigs resulted in no effect on growth or feed efficiency. However, increases in water intake were reported along with temporary mild diarrhea and less firm feces for pigs offered the greater TDS concentrations (Anderson and Stothers, 1978; Paterson et al., 1979).

Total dissolved solids is an inexact measure of water quality. As a general rule, water containing < 1,000 ppm TDS is safe, whereas water containing > 7,000 ppm TDS may present a health risk for pregnant or lactating sows or for pigs under stress and ought not to be offered to swine for consumption (NRC, 1974). A maximum level of 3,000 ppm TDS is recommended for livestock by the Canadian Council of Ministers of the Environment (1987). Because so many different elements can contribute to a high TDS, further chemical analysis is desirable on such water to determine whether the soluble minerals present represent a health risk. However, the values in Table 5-1 can be used as a guide.

The pH of water has little direct relevance to water quality, because almost all samples fall within the acceptable range of 6.5-8.5 (Fraser et al., 1993). However, alterations in pH can have a major effect on chemical reactions involved in the treatment of water. High water pH impairs the efficiency of chlorination, and low water pH may cause precipitation of some antibacterial agents delivered via the water system. Sulfonamides particularly pose a risk (Russell, 1985) and could lead to potential problems with carcass sulfa residues, because precipitated medication in the water lines may leach back into the water after medication has been terminated.

Water hardness is caused by multivalent metal cations, principally calcium and magnesium. Water is considered soft if multivalent cation concentration is < 60 ppm, hard between 120 and 180 ppm, and very hard if multivalent cation concentration is > 180 ppm (Durfor and Becker, 1964). Even very hard water rarely causes problems for swine (NRC, 1980), although it does result in the accumulation of scale in water delivery systems. If this impairs water availability, problems can arise. In one survey, excessively hard water from a region in Quebec, Canada, supplied as much as 29% of a gestating sow's daily requirement for calcium (Filpot and Ouellet, 1988).

Sulfates are the primary cause of water quality problems in well water in many regions of North America. A survey conducted on the Canadian prairies indicated that 25% of wells contained excessive (> 1,000 ppm) quantities of sulfates (McLeese et al., 1991), whereas a survey in Ohio demonstrated a range of sulfate concentrations from 6 to 1,629 ppm (Veenhuizen, 1993) with concentrations correlated with geographic location, depth of well, and TDS. Sulfates are not well tolerated in the gut of the pig, resulting in diarrhea and reduced performance when concentrations are > 7,000 ppm (Anderson et al., 1994). However, lower concentrations (up to 2,650 ppm) have no detrimental effect on pig performance (Veenhuizen et al., 1992; Maenz et al., 1994; Patience et al., 2004). It would seem that pigs can adapt to elevated sulfate concentrations within a few weeks of exposure. This explains why weanling pigs are most susceptible to sulfates because they consume little water before weaning and, as a consequence, are not well adapted. In addition, water odor is not necessarily an indication of poor-quality water. Despite a distinct "rotten egg" smell, water containing 1,900 ppm sulfates did not affect pig performance (DeWit et al., 1987).

Nitrites impair the oxygen-carrying capacity of the blood by reducing hemoglobin to methemoglobin. Heavy applications of nitrogenous fertilizers to land and contamination of runoff water by animal wastes can increase nitrate concentrations in water supplies. Winks et al. (1950) demonstrated that conversion of nitrate to nitrite in the water was necessary for toxicity to occur. They reported mortality in swine with access to well water containing 290-490 ppm of nitrate nitrogen. In agreement, Seerley et al. (1965) considered it unlikely that sufficient nitrite would be formed and consumed in water alone to cause toxicity in swine unless the initial level of nitrate exceeds 300 ppm of nitrate nitrogen. Nitrite nitrogen concentrations > 10 ppm are cause for concern (Task Force on Water Quality Guidelines, 1987). Nitrates and nitrites in water also may impair the use of vitamin A by the pig (Wood et al., 1967). Additional ions may be occasion-

TABLE 5-1 Evaluation of Water Quality for Pigs Based on Total Dissolved Solids

Total Dissolved Solids (ppm)	Rating	Comment
< 1,000	Safe	No risk to pigs.
1,000 to 2,999	Satisfactory	Mild diarrhea in pigs not adapted to it.
3,000 to 4,999	Satisfactory	May cause temporary refusal of water.
5,000 to 6,999	Reasonable	Higher levels for breeding stock should be avoided.
> 7,000	Unfit	Risky for breeding stock and pigs exposed to heat stress.

SOURCE: Adapted from NRC (1974).

ally found in water samples. Safety guidelines are provided in Table 5-2, with more specific information on individual ions in NRC (2005).

In situations where poor-quality water exists, it is essential to determine its impact on animal performance. Often, producers are overly concerned about the diarrhea in situations where animal performance is not impaired. An increased water content of the feces (i.e., a "diarrhea") that is the result of osmotic origin (e.g., an increased amount of sulfates or certain other minerals that are ingested) is categorically different from that which results from microbial contamination and illness. However, when poor water quality does reduce performance, there are a number of procedures (described in the next three paragraphs) that can be implemented to alleviate the problem.

Chlorination disinfects and destroys disease-causing microorganisms. Protozoa and enteroviruses are much more resistant to chlorination than are bacteria (Fraser et al., 1993). The effectiveness of disinfection and the quantity of chlorine required in the water depends on the quantity of nitrites, iron, hydrogen sulfide, ammonia, and organic matter in the water. The presence of organic matter in the water converts the free chlorine to chloramines, which have less disinfecting action. Sodium hypochlorite or laundry bleach (5.25% chlorine solution) is commonly used for chlorination. The higher the pH, the more chlorine that is needed to achieve the same degree of disinfection.

Some changes in the diet may be warranted in response to problems of water quality. A reduction in the salt (NaCl) concentration in the diet is common on farms that use water containing a high mineral (TDS) load. Some salt can usually be removed without causing a problem because most diets contain a reasonable safety margin. However, care is needed to ensure that adequate chloride levels are maintained in the diet because chloride is not usually found in high concentration in poor-quality water.

Hard water may be improved with a water softener. The most common type is an ion-exchange unit in which sodium replaces calcium and magnesium in the water. This reduces the hardness of the water but has no effect on the overall mineral load (TDS) because the water then has a higher sodium content. Reverse osmosis units are available to remove sulfates and nitrates to some degree. However, in addition to the efficiency of any water treatment system, both the capital and operating costs of those systems become factors in decisions related to their use for most livestock operations.

TABLE 5-2 Water Quality Guidelines for Livestock

	Recommended Maximum (ppm)	
Item	TFWQG[a]	NRC[b]
Total dissolved solids	3,000	
Major ions		
Calcium	1,000	—
Nitrate-N + Nitrite-N	100	100
Nitrite-N	10	10
Sulfate	1,000	—
Heavy metals and trace ions		
Aluminum	5.0	—
Arsenic	0.5	0.2
Beryllium	0.1	—
Boron	5.0	—
Cadmium	0.02	0.05
Chromium	1.0	1.0
Cobalt	1.0	1.0
Copper	5.0	0.5
Fluoride	2.0	2.0
Lead	0.1	0.1
Mercury	0.003	0.01
Molybdenum	0.5	—
Nickel	1.0	1.0
Selenium	0.05	—
Uranium	0.2	—
Vanadium	0.1	0.1
Zinc	50.0	25.0

[a]Task Force on Water Quality Guidelines (1987).
[b]NRC (1974).

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6

Minerals

INTRODUCTION

Pigs have a dietary requirement for many inorganic elements. These elements include calcium (Ca), chlorine (Cl), chromium (Cr), copper (Cu), iodine (I), iron (Fe), magnesium (Mg), manganese (Mn), phosphorus (P), potassium (K), selenium (Se), sodium (Na), sulfur (S), and zinc (Zn). Cobalt (Co) also is required in the synthesis of vitamin B_{12} within the gastrointestinal tract but may not be needed in a postabsorptive capacity as such. Pigs may also require other trace elements (i.e., arsenic [As], boron [B], bromine [Br], molybdenum [Mo], nickel [Ni], silicon [Si], tin [Sn], and vanadium [V]) that have been shown to have a physiological role in one or more species (Underwood, 1977; Nielsen, 1984). These elements, however, if required at all, are required at such low levels that their dietary essentiality has not been proven. The inorganic elements are generally determined in feeds and tissues by procedures that involve acid digestion followed by assay via atomic absorption spectrophotometry or inductively coupled plasma spectroscopy. While the assay procedures are not difficult, generally, care is essential for many elements so that contamination does not occur in the collection, handling, and processing of the samples because some elements are ubiquitous in the environment. Specialized laboratory techniques are required for anions.

The functions of these inorganic elements are extremely diverse. They range from structural functions in some tissues to a wide variety of regulatory functions in other tissues, including the efficiency of use of protein and energy via their physical presence as a constituent of various enzymes or as cofactors for enzymatic reactions. Hence, though they may constitute a small part of the diet both physically and economically, they can have a major impact on well-being and on the biological and economic efficiency of swine production. Suggested minimum requirements for the individual elements at various stages of the life cycle are given in tables provided in Chapter 16. Meeting the physiological mineral requirements of the pig will certainly be influenced by the bioavailabilities of minerals in feed ingredients. The subject of bioavailability of minerals is included in *Bioavailability of Nutrients for Animals*, edited by Ammerman et al. (1995).

Several minerals, including antimony (Sb), arsenic (As), cadmium (Cd), fluorine (F), lead (Pb), and mercury (Hg), can be toxic to swine (Carson, 1986). The toxicities and dietary maximum tolerable levels of essential and other mineral elements are described in detail in *Mineral Tolerance of Animals* (NRC, 2005).

MACROMINERALS

Calcium and Phosphorus

Calcium (Ca) and phosphorus (P) play a major role in the development and maintenance of the skeletal system and perform many other physiological functions (Hays, 1976; Peo, 1976, 1991; Kornegay, 1985; Crenshaw, 2001). The requirement estimates for Ca/P in this revision are not determined by a direct assessment of empirical results but, rather, are derived from the nutrient requirement model. Model-generated requirements of Ca and P were compared to the empirical results for assessment of any gross deviance from the literature. The standardized total tract digestible (STTD) P requirement was first estimated for each stage of production and then Ca/STTD P ratios appropriate for each stage of production were applied to derive the estimated Ca requirement. The refinement of requirement estimates and the use of STTD P will allow greater precision in meeting the need of groups of pigs with varying levels of performance while minimizing P levels in excreta. The estimated dietary requirements for Ca and P for maximum growth rate and feed efficiency of pigs from 3 to 135 kg, for gestation and lactation, and for boars are given in Chapter 16, Tables 16-9, 16-12, and 16-13. A review of the literature follows herewith, followed by a brief explanation of the principles of the modeling; more explicit descriptions of the Ca and P modeling are given in Chapter 8.

Peo (1991) indicated that adequate Ca and P nutrition for all classes of swine is dependent upon: (1) an adequate supply of each element in an available form in the diet, (2) a suitable ratio of available Ca and P in the diet, and (3) the presence of adequate vitamin D. A wide Ca-to-P ratio lowers P absorption, resulting in reduced growth and bone calcification, especially if the diet is marginal in P (Vipperman et al., 1974; Doige et al., 1975; van Kempen et al., 1976; Reinhart and Mahan, 1986; Hall et al., 1991; De Wilde and Jourquin, 1992; Eeckhout et al., 1995). The ratio is less critical if the diet contains excess P (Prince et al., 1984; Hall et al., 1991). A suggested ratio of total Ca to total P for grain-soybean meal diets is between 1:1 and 1.25:1. A narrower Ca-to-P ratio probably results in more efficient utilization of P. An adequate amount of vitamin D is also necessary for proper metabolism of Ca and P, but a very high level of vitamin D can mobilize excessive amounts of Ca and P from bones (Hancock et al., 1986; Jongbloed, 1987). Recent research (Lauridsen et al., 2010) has demonstrated that the vitamin D requirement for sows is underestimated. This finding has resulted in a revised estimate in the vitamin D requirement in this publication, which will impact bone measures that previously may have been attributed to inadequate Ca and/or P levels in the diet.

A considerable amount of research has been conducted to determine the Ca and P requirements of weanling pigs (Rutledge et al., 1961; Combs and Wallace, 1962; Combs et al., 1962, 1966; Miller et al., 1962, 1964a,b, 1965a,b,c; Menehan et al., 1963; Zimmerman et al., 1963; Blair and Benzie, 1964; Mudd et al., 1969; Coalson et al., 1972, 1974; Mahan et al., 1980; Mahan, 1982) and growing-finishing swine (Chapman et al., 1962; Libal et al., 1969; Cromwell et al., 1970, 1972; Stockland and Blaylock, 1973; Doige et al., 1975; Pond et al., 1975, 1978; Fammatre et al., 1977; Kornegay and Thomas, 1981; Thomas and Kornegay, 1981; Maxson and Mahan, 1983; Combs et al., 1991a,b; Ekpe et al., 2002; Ruan et al., 2007; Hu et al., 2010; Partanen et al., 2010; Saraiva et al., 2011). Although there is extensive literature evaluating Ca and P in growing pigs, only a limited number was deemed appropriate from which to determine an empirical P requirement. Data were included when there were three or more levels of dietary P and when the average daily gain (ADG) response to dietary P was curvilinear to allow determination of a requirement estimate. From those data, the diet composition at the requirement estimate was obtained and apparent total tract digestibility (ATTD) and STTD values for each feedstuff (as defined in this publication) were applied to the diet composition to estimate ATTD and STTD P percentage using procedures similar to those described in Chapter 2 for amino acids. Table 6-1 summarizes these data based upon average body weight (BW) and additionally provides an estimate of ADG, ADFI, the ME (kcal/kg) of the diet, and an estimate of the ATTD and STTD P value at this rate of gain. Percent ATTD and STTD "requirements" are depicted in Figure 6-1 with the average grams of ATTD P and STTD P per kilogram gain being 5.7 and 6.7 g, respectively.

Dietary concentrations of Ca and P that result in maximum growth rate are not necessarily adequate for maximum bone mineralization. The requirements for maximizing bone strength and bone ash content are at least 0.1 percentage units higher than the requirements for maximum rate and efficiency of gain (Cromwell et al., 1970, 1972; Mahan et al., 1980; Crenshaw et al., 1981; Kornegay and Thomas, 1981; Mahan, 1982; Maxson and Mahan, 1983; Koch et al., 1984; Combs et al., 1991a,b). However, maximization of bone strength by feeding large amounts of Ca and P to growing pigs does not necessarily improve structural soundness (Pointillart and Gueguen, 1978; Kornegay and Thomas, 1981; Kornegay et al., 1981a,b, 1983; Calabotta et al., 1982; Brennan and Aherne, 1984; Lepine et al., 1985; Eeckhout et al., 1995).

The dietary Ca and P requirements, expressed as a percentage of the diet, may be slightly higher for gilts than for barrows (Thomas and Kornegay, 1981; Calabotta et al., 1982). The Ca and P requirements of the developing boar are greater than those of the barrow and gilt (Hickman et al., 1983; Kesel et al., 1983; Hansen et al., 1987). When lean

TABLE 6-1 Empirical Phosphorus Requirement Estimates in Growing-Finishing Pigs as Affected by Body Weight

	BW, kg			Performance		Diet	ATTD		STTD	
Reference	Mean	Initial	Final	ADG	ADFI	ME	%	g/kg gain	%	g/kg gain
Coalson et al. (1972)	11.4	2.9	19.8	410	683	3,555	0.334	5.56	0.372	6.20
Mahan et al. (1980)	13.5	7.0	20.0	350	680	3,312	0.285	5.55	0.335	6.51
Ruan et al. (2007)	30.4	21.4	39.3	668	1,640	3,274	0.292	7.18	0.356	8.75
Maxson and Mahan (1983)	37.5	18.3	56.7	620	1,690	3,345	0.223	6.07	0.263	7.18
Ekpe et al. (2002)	42.4	23.7	61.1	895	1,916	3,216	0.238	5.09	0.277	5.94
Partanen et al. (2010)	45.0	25.0	65.0	864	1,814	2,868	0.256	5.38	0.294	6.18
Hastad et al. (2004)	45.9	33.8	57.9	861	1,514	3,319	0.249	4.37	0.289	5.09
Cromwell et al. (1970)	55.2	18.1	92.2	783	2,470	3,324	0.185	5.82	0.221	6.98
Bayley et al. (1975a)	57.5	25.0	90.0	823	2,410	3,324	0.185	5.41	0.223	6.52
Thomas and Kornegay (1981)	64.0	25.0	103.0	800	2,510	3,291	0.196	6.13	0.231	7.25
Thomas and Kornegay (1981)	66.0	25.0	107.0	810	2,520	3,291	0.196	6.08	0.231	7.19
Hastad et al. (2004)	98.9	88.5	109.3	742	2,143	3,314	0.206	5.96	0.240	6.93

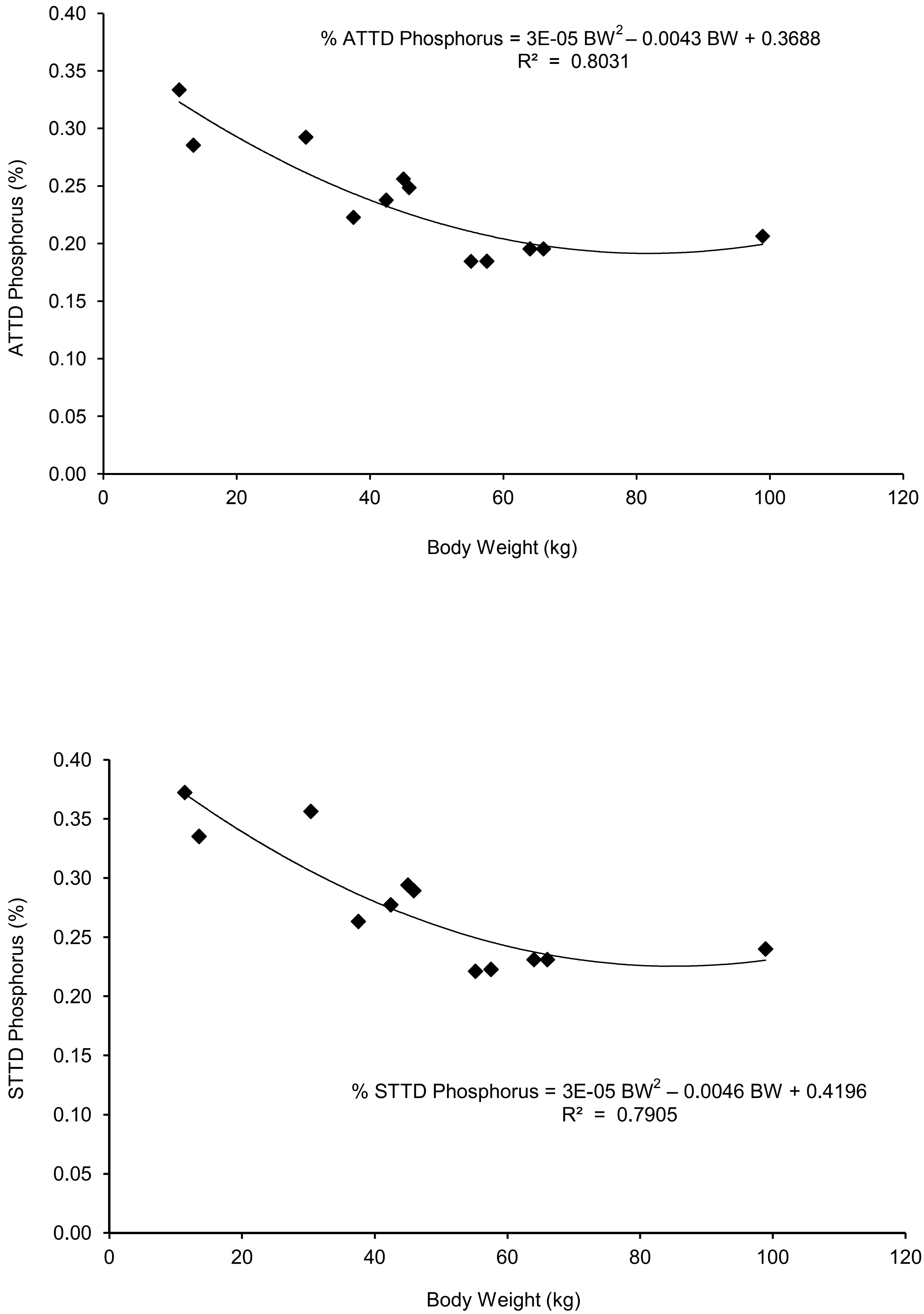

FIGURE 6-1 An empirical estimate of the ATTD and STTD P requirement as a function of body weight. Individual data points represent computed values from Table 6-1.

growth rate is increased by treating pigs with porcine somatotropin, the dietary requirement, expressed as percentage of the diet, increases due to the reduced daily feed intake resulting from porcine somatotropin treatment (Weeden et al., 1993a,b; Carter and Cromwell, 1998a,b). There is also strong evidence that pigs treated with porcine somatotropin require greater daily amounts of Ca and P to maximize growth performance, bone mineralization, and carcass leanness than untreated pigs (Carter and Cromwell, 1998a,b).

Kornegay et al. (1973), Harmon et al. (1974b, 1975), Nimmo et al. (1981a,b), Mahan and Fetter (1982), Arthur et al. (1983a,b), Grandhi and Strain (1983), Kornegay and Kite (1983), Maxson and Mahan (1986), Mahan et al. (2009), and Everts et al. (1998a,b) have investigated the Ca and P requirements of breeding swine. Feeding of dietary levels of Ca and P sufficient to maximize bone mineralization in gilts during early growth and development was shown to improve reproductive longevity in one study (Nimmo et al., 1981a,b) but not in other studies (Arthur et al., 1983a,b; Kornegay et al., 1984). During pregnancy, the physiological requirements for Ca and P increase in proportion to the need for fetal growth and reach a maximum in late gestation (Mahan et al., 2009). During lactation, the requirements are affected by the level of milk production by the sow. Generally, the requirements for Ca and P are based on a feeding level of 1.8-2.0 kg of feed/day during gestation and 5-6 kg of feed/day during lactation. If sows are fed less than 1.8 kg of feed during gestation, the diet has to be formulated to contain sufficient concentrations of Ca and P to meet the daily requirements; alternately, if sows are routinely fed higher amounts of feed because of a need to maintain sow condition scores, which are related more to protein and energy needs, then the Ca and P levels in the diet can be adjusted downward. The voluntary feed intake of lactating sows may be reduced by high environmental temperatures. In this circumstance, assuming that milk production is not decreased, the lactation diet has to be formulated to meet the daily needs of Ca and P. Adequate Ca and P intakes are more critical in first-parity sows than in mature sows (Giesemann et al., 1998) because of needs for skeletal growth in that female.

The form in which P exists in natural feedstuffs influences the efficiency of its utilization. In cereal grains, grain byproducts, and oilseed meals, about 60-75% of the P is organically bound in the form of phytate- or phytin-P (myo-inositol 1,2,3,4,5,6-hexakis dihydrogen phosphate complexed with various cations, protein, and carbohydrates) (Nelson et al., 1968; Lolas et al., 1976; Angel et al., 2002), which is poorly available to the pig (Taylor, 1965; Peeler, 1972; Erdman, 1979; Jongbloed and Kemme, 1990; Pallauf and Rimbach, 1997). The biological availability of P in cereal grains is variable, ranging from less than 15% in corn (Bayley and Thomson, 1969; Miracle et al., 1977; Calvert et al., 1978; Trotter and Allee, 1979a,b; Huang and Allee, 1981; Ross et al., 1983) to approximately 50% in wheat (Miracle et al., 1977; Trotter and Allee, 1979a; Cromwell, 1992). The greater availability of P in wheat and wheat byproducts (Stober et al., 1980a; Hew et al., 1982) is attributed to the presence of a naturally occurring phytase enzyme in wheat (McCance and Widdowson, 1944; Mollgaard, 1946; Pointillart et al., 1984). The P in high-moisture corn or grain sorghum is considerably more available than that in dry grain (Trotter and Allee, 1979b; Boyd et al., 1983; Ross et al., 1983). The P in low-phytic acid corn (modified by the mutant *lpa1* gene) is relatively high (77%) in its bioavailability (Cromwell et al., 1998b), as would be expected in all low-phytate ingredients.

The P in oilseed meals also has a low bioavailability (Tonroy et al., 1973; Miracle et al., 1977; Trotter and Allee, 1979a; Stober et al., 1980b; Harrold, 1981; Ross et al., 1982; Cromwell, 1992). In contrast, the P in protein sources of animal origin is largely inorganic, and most animal protein sources (including milk and blood byproducts) have a high P bioavailability (Cromwell et al., 1976; Hew et al., 1982; Coffey and Cromwell, 1993). The bioavailability of P in meat and bone meal is variable. Some studies indicated that the bioavailability of P in meat and bone meal was somewhat lower (67%) than in most other animal sources (Cromwell, 1992), but other studies showed a relatively high bioavailability (90%; Traylor et al., 2005). Steam pelleting has been shown to improve the bioavailability of phytate P in some studies (Bayley and Thompson, 1969; Bayley et al., 1975b) but not in others (Trotter and Allee, 1979c; Corley et al., 1980; Ross et al., 1983).

Microbial phytase supplementation of high-phytate, cereal grain–oilseed meal diets can result in major improvements in bioavailability of phytate P (Nasi, 1990; Simons et al., 1990; Jongbloed et al., 1992; Pallauf et al., 1992a,b; Cromwell et al., 1993b, 1995; Lei et al., 1993b). As a result, the dietary level of P can be reduced, thereby lowering P excretion by 30-60%. The magnitude of the response to microbial phytase is influenced by the dietary level of available and total P (including phytate P), the amount of supplemental phytase, the Ca-to-P ratio (or level of Ca), and the level of vitamin D (Jongbloed et al., 1993; Düngelhoef et al., 1994; Lei et al., 1994; Kornegay, 1996; Adeola et al., 1998; Johansen and Poulsen, 2003; Selle and Ravindran, 2008; Selle et al., 2009; Kerr et al., 2010; Letourneau-Montminy et al., 2010). Microbial phytase also improves the bioavailability of Ca (Pallauf et al., 1992b; Lei et al., 1993b; Young et al., 1993; Mroz et al., 1994), Fe (Stahl et al., 1999), and Zn (Pallauf et al., 1992a, 1994a,b; Lei et al., 1993a; Revy et al., 2004) and has been reported to improve the digestibility of dietary protein (Ketaren et al., 1993; Mroz et al., 1994; Kemme et al., 1995; Biehl and Baker, 1996). Because phytase releases Zn from the phytate complex, it can result in an increased requirement for minerals such as Cu with which Zn has an antagonistic effect relative to absorption (Zacharias et al., 2003). Pelleting of diets can reduce or destroy phytase activity because of the temperature increases that occur during the pelleting process. Loss of phytase activity has been reported when temperatures exceed 60°C (Jongbloed and Kemme, 1990; Nunes, 1993); such a loss can result in reduced digestibility of P and Ca (Jongbloed and Kemme, 1990).

The P in inorganic P supplements also varies in bioavailability. The P in ammonium, Ca, and sodium phosphates is highly available (Kornegay, 1972b; Hays, 1976; Clawson and Armstrong, 1981; Partridge, 1981; Tunmire et al., 1983; Cromwell, 1992). The P in steamed bone meal is less available than that in mono-dicalcium phosphate (Cromwell, 1992). The P in defluorinated rock phosphate is generally less available than in monocalcium phosphate or monosodium phosphate (Cromwell, 1992; Coffey et al., 1994b) but can vary depending on source and processing (Kornegay and Radcliffe, 1997). The P in calcium phosphates may vary depending on specific form and degree of hydration (Eeckhout and De Paepe, 1997). The P in high-fluorine rock phosphates, soft phosphate, colloidal clay, and Curaçao phosphate is poorly available (Chapman et al., 1955; Plumlee et al., 1958; Harmon et al., 1974b; Hays, 1976).

Little is known about the availability of Ca in natural feedstuffs. Because of the phytic acid content, the bioavailability of Ca in cereal grain-based diets, alfalfa, and various grasses and hays is relatively low (Soares, 1995). However, most feedstuffs contribute so little Ca to the diet that bioavailability of the Ca is of limited consequence. The Ca in calcitic limestone, gypsum, oystershell flour, fish bone meal, skim milk powder, aragonite, and marble dust is highly available (Pond et al., 1981; Ross et al., 1984; Pointillart et al., 2000; Malde et al., 2010), but the Ca in dolomitic limestone is only 50-75% available (Ross et al., 1984). Particle size (up to 0.5 mm in diameter) seems to have little effect on Ca availability (Ross et al., 1984). Pig data are not available, but on the basis of poultry data, the Ca in dicalcium phosphate, tricalcium phosphate, defluorinated phosphate, calcium gluconate, calcium sulfate, and bone meal is highly available, generally 90-100%, when compared with the Ca in calcium carbonate (Baker, 1991; Soares, 1995).

Signs of Ca or P deficiency are similar to those of vitamin D deficiency. They include reduced growth and poor bone mineralization, resulting in rickets in young pigs and osteomalacia in older swine. A problem of Ca- or P-deficient sows that can occur is a paralysis of the hind legs, called posterior paralysis. The problem occurs most frequently toward the end, or just after the end, of lactation in sows producing high levels of milk.

Excess levels of Ca and P may reduce performance of pigs (Reinhart and Mahan, 1986; Hall et al., 1991), and the effect is greater when the Ca:P ratio is increased. Excess Ca not only decreases the utilization of P but also increases the pig's requirement for Zn in the presence of phytate (Luecke et al., 1956; Whiting and Bezeau, 1958; Morgan et al., 1969; Oberleas, 1983). When the molar ratio of cations (Zn and Ca) was 2:1 or 3:1 with phytate, the formation of an insoluble complex was much greater (Oberleas and Harland, 1996).

The Basis for a Factorial Estimation of P and Ca Requirements

In this revised edition a modeling approach is used to estimate the STTD P and total dietary Ca requirements of growing-finishing pigs and sows. The main modeling principles have been described in detail previously (Jongbloed et al., 1999, 2003; Jondreville and Dourmad, 2005; GfE, 2008). The main determinants of P requirements that are considered include (1) maximum rates of whole-body P retention, (2) P retention in products of conceptus, (3) P output with milk, (4) basal endogenous gut P losses, (5) minimum urinary P losses, (6) marginal efficiency of using STTD P intake for P retention, and, for growing-finishing pigs only, and (7) P requirements for maximum growth performance as a proportion of P requirements for maximum whole-body P retention. Because of a lack of data, Ca requirements are derived simply and directly from STTD P requirements using unique and fixed ratios between STTD P and total Ca requirements for growing-finishing pigs, gestating sows, and lactating sows, respectively. A preferred ratio would have been a ratio between digestible Ca and digestible P, but, again, because of lack of data, the ratios between total Ca and STTD P are used herein. The actual parameters and equations that are used to represent P and Ca utilization and requirements are presented in Chapter 8. An evaluation of model-generated estimates of P and Ca requirements is provided in Chapter 8 as well.

In growing-finishing pigs, whole-body P mass, and thus the maximum rate of whole-body P retention, is estimated from whole-body protein mass (e.g., Hendriks and Moughan, 1993; Pettey, 2004; Hinson, 2005). This is in contrast to the approaches presented by Jongbloed et al. (1999, 2003), Jondreville and Dourmad (2005), and GfE (2008), in which live or empty body weight is used to estimate whole-body P mass. Based on a review of available data a clear and close relationship between whole-body P mass and whole-body N mass was established (Figure 6-2; Cromwell et al., 1970; Coalson et al., 1972; Fammatre et al., 1977; Mahan et al., 1980; Crenshaw et al., 1981; Mahan and Fetter, 1982; Maxson and Mahan, 1983; Reinhart and Mahan, 1986; Coffey et al., 1994b; Eeckhout et al., 1995; O'Quinn et al., 1997; Ekpe et al., 2002; Hastad et al., 2004; Pettey et al., 2006; Ruan et al., 2007; Hinson et al., 2009), which appears largely unaffected by pig genotype and gender. This approach to estimating P retention and requirements is consistent with observed effects of gender and lean growth potential on P requirements, which were mentioned in the previous section.

Phosphorus retention in the sow's body is related to changes in maternal body protein mass, and based on the P-to-protein ratio in muscle protein, as outlined by Jongbloed et al. (1999, 2003; ratio 0.0096). The same relationship is used to estimate P mobilization from the body of lactating sows that are in a negative protein balance. In gestating sows, P retention in bone tissue is considered as well, using values that decrease with parity from 2.0 g/day in parity

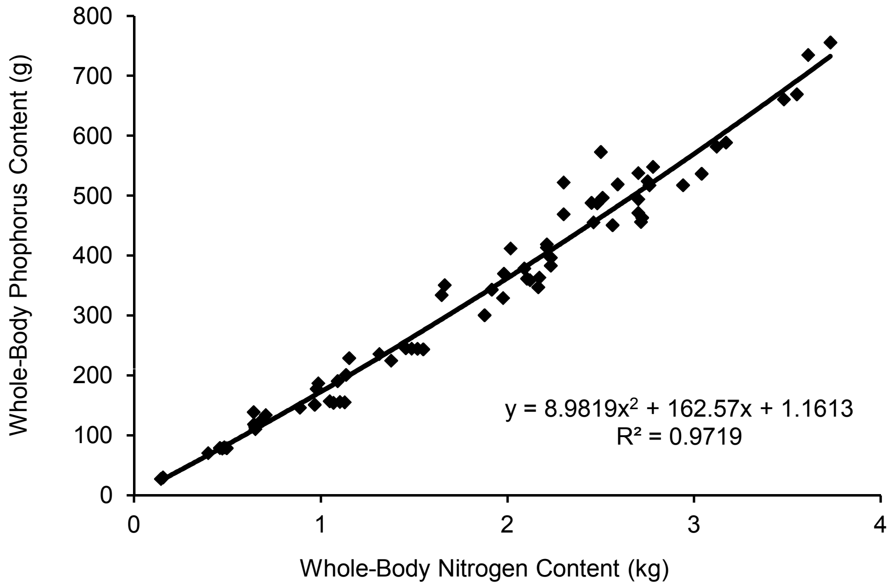

FIGURE 6-2 Relationship between whole-body phosphorus and whole-body nitrogen content in growing-finishing pigs. Individual data points represent treatment means.

1 to 0.8 g/day in parity 4 and older sows. These values are slightly higher than the values suggested by Jongbloed et al. (2003; 1.5 in parity 1 to 0.2 g/day in parity 4) that are based on limited data. Phosphorus retention in conceptus is represented as described by Jongbloed et al. (1999) and Jondreville and Dourmad (2005). As previously stated, it has been well established that total dietary P requirements for maximum growth performance are lower (approximately 0.10 percentage units) than requirements for maximum P retention. It was thus estimated that the STTD P requirements for maximum growth performance in growing-finishing pigs are 0.85 of those for maximum P retention. The starting point for the 0.85 estimate was the 0.10 percentage unit difference in total P requirement. Iterative runs of the computer model with various estimates revealed that 0.85 provided the best fit with the limited empirical data that were available.

In a manner that is consistent with Jondreville and Dourmad (2005), the P output with milk is predicted from milk N output. Based on a review of the literature, the ratio between P and N in milk is rather constant across studies at 0.196 (Boyd et al., 1982; Coffey et al., 1982; Mahan and Fetter, 1982; Hill et al., 1983b; Kalinowski and Chavez, 1984; Miller et al., 1994; Park et al., 1994; Farmer et al., 1996; Seynaeve et al., 1996; Jurgens et al., 1997; Giesemann et al., 1998; Tilton et al., 1999; Lyberg et al., 2007; Peters and Mahan, 2008; Leonard et al., 2010; Peters et al., 2010). This value is very similar to the value of 0.194 used by Jondreville and Dourmad (2005).

To reduce the impact of dietary P level on total tract P digestibility the concept of STTD is used, in a manner that is consistent with standardization of ileal amino acid digestibility values (Chapter 13). Based on a review of the literature and observations of pigs fed P-free diets the basal endogenous fecal P losses are estimated to be 190 mg per kg dry matter intake (Chapter 13). In addition to basal fecal P losses, minimal urinary losses contribute to maintenance P requirements. Minimal urinary P losses are related to body weight as outlined by Jongbloed et al. (1999, 2003) and Jondreville and Dourmad (2005), and a value of 7 mg per kg body weight has been adopted for growing-finishing pigs and sows (Jondreville and Dourmad, 2005).

According to nutrient balance observations on individual growing pigs, the maximum marginal efficiency of using digestible P intake for whole-body P retention is approximately 95% when P intake is slightly below requirements for maximum P retention (Rodehutscord et al., 1998; Pettey et al., 2006; Nieto et al., 2008; Stein et al., 2008). Incremental P intake that is not retained contributes to endogenous fecal and urinary P losses. However, because of between-animal variability, this efficiency is lower in groups of pigs than in individual animals (e.g., Pomar et al., 2003). Therefore, this maximum efficiency is reduced to 0.77, in a manner that is quantitatively consistent with adjustments for amino acid utilization in finishing pigs and gestating sows (Chapter 2). Because of lack of information, this efficiency value is assumed similar for growing-finishing pigs, gestating sows, and lactating sows.

Sodium and Chlorine

Sodium (Na) and chlorine/chloride (Cl) are the principal extracellular cation and anion, respectively, in the body.

Chloride is the chief anion in gastric secretions. Mahan et al. (1996) reported that weanling pigs fed diets containing dried whey or dried plasma (both are relatively high in Na) responded to added Na as NaCl or Na phosphate and to added Cl as hydrochloric acid. A subsequent study (Mahan et al., 1999b) also demonstrated growth and feed efficiency responses to each, particularly Cl; a digestibility study demonstrated improved N digestibility with added Cl. Their results indicate that early-weaned pigs require more Na and Cl, especially in the initial 7-14 days postweaning. In preference studies, Monegue et al. (2011) were able to show that newly weaned pigs, especially barrows, self-select diets higher in salt and that the preference for higher levels of salt diminishes after 2 weeks postweaning. Thus, the estimated dietary Na and Cl requirements have been increased to 0.40/0.50%, 0.35/0.45%, and 0.28/0.32% for the 5- to 7-kg, 7- to 11-kg, and 11- to 25-kg body weight categories, respectively.

The dietary Na requirement of growing-finishing pigs historically has been thought to be no greater than 0.08-0.10% of the diet (Meyer et al., 1950; Alcantara et al., 1980; Honeyfield and Froseth, 1985; Honeyfield et al., 1985; Kornegay et al., 1991). The dietary Cl requirement is less well defined but also was thought to be no higher than 0.08% for the growing pig (Honeyfield and Froseth, 1985; Honeyfield et al., 1985). Based on this perspective, a level of 0.20-0.25% added NaCl would have met the dietary Na and Cl requirements for growth in growing-finishing pigs fed a corn–soybean meal diet (Hagsten and Perry, 1976a,b; Hagsten et al., 1976). However, recent dose evaluations of the effect of added NaCl from 0.10 to 0.60% (Yin et al., 2008) clearly demonstrate that both apparent and true P digestibility is maximized at 0.40% added NaCl; thus, as with the weanling pig, digestibility responses may require greater levels of one of these minerals in the grower stage, and perhaps the finisher stage, as well.

The Na and Cl requirements of breeding animals are not well established. The results of one study suggested that 0.3% dietary NaCl (0.12% Na) was not sufficient for pregnant sows (Friend and Wolynetz, 1981). In a regional study, pig birth weights and weaning weights were reduced when NaCl was reduced from 0.50 to 0.25% during gestation and lactation for two or more parities (Cromwell et al., 1989a). Based upon the Na content of sow's milk, which is 0.03-0.04% (ARC, 1981), the dietary Na requirement is approximately 0.05 percentage unit greater during lactation than during gestation. Until more definitive information is available, NaCl additions of 0.4% to gestation diets and 0.5% to lactation diets are suggested.

The availability of Na and Cl in most feed ingredients is believed to be 90-100% (Miller, 1980). The Na in water, which in coastal regions can be as high as 184 mg/L, and in defluorinated phosphate, is highly available for pigs (Kornegay et al., 1991).

A deficiency of Na or Cl reduces the rate and efficiency of growth in pigs. In contrast, swine can tolerate high dietary levels of NaCl (NRC, 2005), provided they have access to ample nonsaline drinking water. If nonsaline water is limited or if the level of NaCl in water is high, toxicity can result. The high Na ion concentration is responsible for adverse physiological reactions, apparently because of a disturbance in water balance. The signs of Na toxicity include nervousness, weakness, staggering, epileptic seizures, paralysis, and death (Bohstedt and Grummer, 1954; Carson, 1986).

Sodium, K, and Cl are the primary dietary ions that influence electrolyte balance and acid-base status of animals. Under most circumstances, dietary mineral balance is expressed as milliequivalents (mEq) of Na plus K minus Cl ions (Na + K – Cl; Mongin, 1981) and is often referred to as electrolyte balance. Patience and Wolynetz (1990) suggested that Ca, Mg, S, and P ions also be included in the calculation of electrolyte balance. The optimal electrolyte balance in the diet for pigs is about 250 mEq of excess cations (Na + K – Cl)/kg of diet according to Austic and Calvert (1981), Golz and Crenshaw (1990), Haydon et al. (1993), and Dersjant-Li et al. (2001); however, optimal growth can occur over the range of 0 to 600 mEq/kg of diet (Patience et al., 1987; Kornegay et al., 1994). If a deficiency of Na, K, or Cl occurs in the diet, then the relationship, Na + K – Cl, as an estimate of electrolyte balance, does not accurately predict dietary levels for optimum growth (Mongin, 1981).

Magnesium

Magnesium (Mg) is a cofactor in many enzyme systems and is a constituent of bone. The Mg requirement of artificially reared pigs fed milk-based semipurified diets is between 300 and 500 mg/kg (i.e., 0.03-0.05%) of diet (Mayo et al., 1959; Bartley et al., 1961; Miller et al., 1965b,c,d). Milk contains adequate Mg to meet the requirement of suckling pigs (Miller et al., 1965b,c). The Mg requirement of weanling-growing-finishing swine is probably not higher than that of the young pig. The Mg in a corn–soybean meal diet (0.14-0.18%) is apparently adequate (Svajgr et al., 1969; Krider et al., 1975), although some research suggests that the Mg in natural ingredients is only 50-60% available to the pig (Miller, 1980; Nuoranne et al., 1980).

The Mg requirement of breeding animals is not well established. Harmon et al. (1976) fed semipurified diets containing 0.04 and 0.09% Mg to sows during gestation, followed by 0.015 and 0.065% Mg during lactation in a single-parity study. They observed no difference in reproductive or lactational performance. However, in a balance study, sows fed the low level of Mg during lactation were in negative Mg balance.

In order of appearance, signs of Mg deficiency include hyperirritability, muscular twitching, reluctance to stand, weak pasterns, loss of equilibrium, and tetany followed by death (Mayo et al., 1959; Miller et al., 1965b); Mg deficiency is exacerbated by high Mn content of the diet (Miller et al., 2000).

Potassium

Potassium (K) is the third most abundant mineral in the body of the pig, surpassed only by Ca and P (Manners and McCrea, 1964) and is the most abundant mineral in muscle tissue (Stant et al., 1969). Potassium is involved in electrolyte balance and neuromuscular function. It also serves as the monovalent cation to balance anions intracellularly, as part of the Na-K pump physiological mechanism.

The dietary K requirement of pigs from 1 to 4 kg body weight is estimated to be between 0.27 and 0.39% (Manners and McCrea, 1964); from 5 to 10 kg, 0.26-0.33% (Jensen et al., 1961; Combs et al., 1985); at 16 kg, 0.23-0.28% (Meyer et al., 1950); and from 20 to 35 kg, less than 0.15% (Hughes and Ittner, 1942; Mraz et al., 1958). No estimates are available for finishing or breeding pigs. The content of K in most practical diets is normally adequate to meet these requirements for all classes of swine. The K in corn and soybean meal is 90-97% available (Combs and Miller, 1985).

Dietary potassium is interrelated with dietary Na and Cl. Increasing dietary Cl from 0.03 to 0.60% in purified diets reduced growth rate of young pigs when the diet contained 0.1% K, but it increased growth rate when the diet contained 1.1% K (Golz and Crenshaw, 1990). The interactive effect of dietary K and Cl seems to be an indirect effect on the excretion and retention of additional cations and anions, particularly ammonium and phosphate. The effects on growth are mediated via mechanisms involving renal ammonium ion metabolism (Golz and Crenshaw, 1991).

Signs of K deficiency include inappetance, rough hair coat, emaciation, inactivity, and ataxia (Jensen et al., 1961). Electrocardiograms of K-deficient pigs showed reduced heart rate and increased electrocardial intervals (Cox et al., 1966). Necropsy of affected pigs revealed no unique gross pathology.

The toxic level of K is not well established. Pigs can tolerate up to 10 times the K requirement if plenty of drinking water is provided (Farries, 1958). However, some liquid coproducts available to the swine industry have higher levels of K that can reduce feed intake and growth and, while feed efficiency and carcass measures may not be affected, caution has to be exercised because the high K intake from these coproducts was associated with signs of kidney damage, such as discolorations and deposits of calcium salts (Guimaraes et al., 2009). Intravenous infusion of KCl in pigs resulted in abnormal electrocardiograms (Coulter and Swenson, 1970).

Sulfur

Sulfur (S) is an essential element. The S provided by the S-containing amino acids has historically seemed adequate to meet the pig's needs for synthesis of S-containing compounds, such as taurine, glutathione, lipoic acid, and chondroitin sulfate, because additions of inorganic sulfate to low-protein diets have not been beneficial (Miller, 1975; Baker, 1977). However, there is more current concern about excesses of S in the diet because various corn coproducts may have increased total S (Kerr et al., 2008) that could serve as a substrate for increased H_2S production by sulfate-reducing bacteria, thereby affecting gastrointestinal health and function. Kerr et al. (2011), in two experiments with 13-kg pigs fed inorganic S ranging from 0.21 to 1.21%, observed a linear reduction in daily gain and the higher dietary S levels did alter some inflammatory mediators and intestinal bacteria. Perez et al. (2011b) fed 9-kg pigs inorganic S ranging from 0.2 to 0.6% and also observed a linear reduction in daily gain. In both studies the reduction in growth rate was primarily due to an effect of diet on feed intake.

MICRO/TRACE MINERALS

Chromium

Chromium (Cr) is involved in carbohydrate, lipid, protein, and nucleic acid metabolism (Nielsen, 1994). A primary metabolic role for which biologically active forms of Cr are known is alteration of tissue sensitivity to insulin that is manifest either as alterations in serum glucose or insulin levels. A "glucose tolerance factor" that contained Cr was reported to potentiate insulin activity in swine and to be biologically active (Steele et al., 1977). Chromium added as chromium tripicolinate was then reported by Evock-Clover et al. (1993) to lower serum insulin and glucose concentrations in growing pigs. Lindemann et al. (1995) reported lower postfeeding serum insulin values as well as lower insulin-to-glucose ratios for fasted gestating sows fed chromium tripicolinate than for fasted control sows. A response of improved insulin efficiency with chromium tripicolinate after consumption of a normal meal was also demonstrated by Garcia et al. (1997). This effect on tissue sensitivity to insulin is not always seen in a normal feeding situation and alterations in serum glucose concentrations were not observed by Page et al. (1993). Using classic methodologies of intravenous glucose tolerance tests (IVGTT) and insulin challenge tests (IVICT), responses are more consistent. These tests have demonstrated Cr effects on glucose or insulin levels (and/or kinetics) in pigs with supplementation of chromium tripicolinate (Amoikon et al., 1995; Matthews et al., 2001), chromium yeast (Guan et al., 2000), chromium propionate (Matthews et al., 2001), and chromium methionine (Fakler et al., 1999). These effects of Cr on glucose and insulin are mediated through its role as a constituent of a low-molecular-weight chromium-binding substance that has a variety of functions (Davis et al., 1996; Davis and Vincent, 1997) and is now termed chromodulin (Vincent, 2001). Bioavailable forms of Cr have also been reported to affect aspects of growth hormone secretion (Wang et al., 2008, 2009).

In the weanling pig there have been fewer studies conducted than in the growing-finishing pig. The supplementation of an organic source of Cr has generally not provided improvements in growth performance and has variable effects on aspects of the immune system (van Heugten and Spears, 1997; Lee et al., 2000a,b; Tang et al., 2001; van de Ligt et al., 2002a,b; Lien et al., 2005). With growing-finishing pigs, interest has focused on the potential use of organic forms of chromium to increase carcass leanness (i.e., increase muscling and/or reduce estimates of fat content) with reports of positive responses (Page et al., 1993; Boleman et al., 1995; Lindemann et al., 1995; Mooney and Cromwell, 1995, 1997; Min et al., 1997; Lien et al., 2001; Urbanczyk et al., 2001; Xi et al., 2001; Wang and Xu, 2004; Jackson et al., 2009; Park et al., 2009). However, others have reported no responses in carcass leanness to supplemental Cr in organic forms (Harris et al., 1995; Mooney and Cromwell, 1996; Lemme et al., 1999). In addition to the overall effects on the carcass, there have been reports of improved pork quality with the addition of Cr from chromium propionate (Matthews et al., 2003, 2005; Shelton et al., 2003; Jackson et al., 2009). The reported effects on daily gain and feed efficiency in these studies have been inconsistent. There are two reports of improved nutrient digestibility with organic Cr (Kornegay et al., 1997; Park et al., 2009). The lack of a consistent response may be related to Cr levels of diets, form of Cr, Cr status of pig, and amino acid levels of the diet (Lindemann, 2007). The total Cr content of a corn–soybean diet can range from 750 to 3,000 ppb, but most of this is probably unavailable. Chromium, especially inorganic forms, is poorly absorbed from the gastrointestinal tract. The amount of inorganic Cr absorbed ranges from 0.4 to 3%, according to a review by Anderson (1987).

Larger litters at birth for sows fed 200 ppb as chromium tripicolinate were reported by Lindemann et al. (1995), which has since been confirmed by Hagen et al. (2000), Lindemann et al. (2000, 2004), and Real et al. (2008) but was not observed by Campbell (1998). The response of increased litter size has also been observed with chromium methionine (Perez-Mendoza et al., 2003). Other reproductive responses such as days to return to estrous, conception and farrowing rates, and culling rate have been inconsistent. Because muscle is a target tissue for insulin and constitutes the single largest body tissue, Lindemann et al. (2004) examined the effect of Cr intake per unit body weight on reproductive performance. The group calculated the amount of Cr received by growing animals in studies that had evaluated responses in IVGTTs and IVICTs to supplemental Cr. The value they computed was about 7.5 µg Cr/kg BW per day. When this value is extended to reproducing animals (based on their size and feed intake), it would take about 500-600 ppb of supplemental Cr in the diet to supply an equivalent amount per unit BW to that received by growing animals. The reproductive study they then conducted used multiple levels of supplemental Cr from chromium tripicolinate (0, 200, 600, and 1,000 ppb) for a minimum of two parities. They observed a quadratic response in litter size to Cr supplementation that was highest at 600 ppb of supplementation, confirming the hypothesis that supplementation of nutrients to reproducing animals that are limit fed may need to be assessed in a manner other than amount supplied per unit of diet or amount supplied per day.

Trivalent and hexavalent are the two most common forms of Cr; both are stable. Hexavalent Cr is much more toxic than trivalent Cr, which is believed to be the essential trace mineral (Anderson, 1987; Mertz, 1993). Maximum tolerable dietary levels for swine were set at 3,000 ppm Cr as the oxide and 100 ppm for soluble trivalent Cr sources (NRC, 2005); hexavalent Cr is a toxicant that is inappropriate for inclusion in swine diets. Studies in which pigs were fed 5,000 ppb of Cr from chromium tripicolinate, chromium propionate, chromium yeast, or chromium methionine for 75 days prior to slaughter failed to show any negative response in growth performance, carcass measures, and clinical chemistry. Tan et al. (2008) fed up to 3,200 ppb of Cr as chromium tripicolinate for 80 days (approximately the entire growing-finishing period); while alteration in activity of some antioxidant enzymes was observed, the results suggested that long-term exposure to different doses of chromium tripicolinate in feed did not increase the formation of biomarkers of oxidative damage in growing-finishing pigs. These results suggest that supplementation at 200 ppb Cr (the most common level of supplementation permitted) is not an item of concern.

No quantitative estimate of the Cr requirement has been established for pigs. The addition of Cr to livestock diets is regulated in most countries relative to the form(s) and inclusion level(s) that are allowed; feed formulators have to be aware of restrictions that may affect swine diets. A review on Cr was published by the NRC (1997); a more recent review of Cr in farm livestock can be found in Lindemann (2007).

Cobalt

Cobalt (Co) is a component of vitamin B_{12} (Rickes et al., 1948). Dietary Co has been thought to be used only by the intestinal microflora of the pig to synthesize vitamin B_{12}. Intestinal synthesis is more important if dietary vitamin B_{12} is limiting (Klosterman et al., 1950; Kline et al., 1954). Because the use of supplemental vitamin B_{12} in practical diets is a routine practice, discussion and research related to potential Co need is limited.

While there is no evidence that pigs have an absolute requirement for Co other than for its role in vitamin B_{12}, Co can substitute for Zn in the enzyme carboxypeptidase and for part of the Zn in the enzyme alkaline phosphatase. Hoekstra (1970) reported that supplemental Co prevented lesions associated with a Zn deficiency. Stangl et al. (2000) reported that Co supplementation at 1 ppm to diets unsupplemented with B_{12} did not result in any changes in serum or liver B_{12} values but restored alterations in liver catalase and serum glutathione peroxidase values resulting from the B_{12} deficient diets, which suggests that there may be aspects of Co metabolism yet to be understood.

A level of 400 ppm Co was toxic to the young pig (Huck and Clawson, 1976) and may cause inappetance, stiff-leggedness, humped back, incoordination, muscle tremors, and anemia. Cobalt concentration in the kidney and liver increased linearly and growth decreased linearly over a 4- to 5-week period as 0, 150, and 300 ppm Co were added to a basal diet containing < 2 ppm Co (Kornegay et al., 1995). Selenium, vitamin E, and cysteine provide some protection against toxicity from excessive levels of dietary Co (Van Vleet et al., 1977), but growth-stimulating levels of Cu may aggravate the growth reduction caused by Co (Kornegay et al., 1995).

Copper

The pig requires copper (Cu) for the synthesis of hemoglobin and for the synthesis and activation of several oxidative enzymes necessary for normal metabolism (Miller et al., 1979). A level of 5-6 ppm in the diet is adequate for the neonatal pig (Okonkwo et al., 1979; Hill et al., 1983a). The requirement for later stages of growth is probably no greater than 5-6 ppm. Definitive information on requirements during gestation and lactation are scarce. Lillie and Frobish (1978) suggested that 60 ppm of Cu fed to sows improved pig weights at birth and at weaning, but this response may have resulted from the pharmacological effect of high dietary Cu. Kirchgessner et al. (1980) reported that pregnant sows fed 2 ppm of Cu had reduced ceruloplasmin and farrowed more stillborn pigs than sows fed 9.5 ppm of Cu. In a balance study, Kirchgessner et al. (1981) estimated the Cu requirement of pregnant sows at 6 ppm. In an examination of supplementation during lactation, Yen et al. (2005) concluded that an additional 14 mg/day of Cu from a Cu-proteinate compound increased the percentage bred by day 7 postweaning.

Cu salts with high biological availabilities include the sulfate, carbonate, and chloride salts (Miller, 1980; Cromwell et al., 1998a). The Cu in cupric sulfide and cupric oxide is poorly available to the pig (Cromwell et al., 1978, 1989b). Organic complexes of Cu seem to have equal bioavailability to Cu sulfate in several trials (Bunch et al., 1965; Zoubek et al., 1975; Stansbury et al., 1990; Coffey et al., 1994a; Apgar et al., 1995; Apgar and Kornegay, 1996). However, in two trials reported by Coffey et al. (1994a) and Zhou et al. (1994a), growth performance was greater in pigs fed growth promotion levels of Cu from a Cu lysine complex than those fed Cu sulfate.

A deficiency of Cu leads to poor Fe mobilization; abnormal hemopoiesis; and poor keratinization and synthesis of collagen, elastin, and myelin. Cu deficiency signs include a microcytic, hypochromic anemia; bowing of the legs; spontaneous fractures; cardiac and vascular disorders; and depigmentation (Hart et al., 1930; Elvehjem and Hart, 1932; Teague and Carpenter, 1951; Follis et al., 1955; Carnes et al., 1961; Hill et al., 1983a).

Cu may be toxic when dietary levels in excess of 250 ppm are fed for extended periods of time (NRC, 1980). Toxicity signs include reduced hemoglobin levels and jaundice, which are the results of excessive Cu accumulation in the liver and other vital organs. Reduced dietary levels of Zn and Fe or high levels of dietary Ca accentuate Cu toxicity (Suttle and Mills, 1966a,b; Hedges and Kornegay, 1973; Prince et al., 1984). The maximum tolerable level for pigs is 250 ppm of diet (NRC, 2005).

When fed at 100-250 ppm, Cu (as Cu sulfate) stimulates growth in pigs (Barber et al., 1955a; Braude, 1967; Wallace, 1967; Cromwell et al., 1981; Kornegay et al., 1989; Cromwell, 1997). The growth response to Cu in young pigs is independent of, and in addition to, the growth response to other antibacterial agents (Stahly et al., 1980; Roof and Mahan, 1982; Edmonds et al., 1985; Cromwell, 1997). The response to high levels of Cu may be enhanced by added fat (Dove and Haydon, 1992; Dove, 1993a, 1995). The continuous feeding of high Cu levels (250 ppm added to diets already containing a normal addition of 9 ppm Cu) to sows for up to six consecutive gestation-lactation cycles did not have any apparent negative effects on reproductive performance, in spite of rather large increases in liver and kidney Cu concentrations (Cromwell et al., 1993a). In fact, advantages for the high-Cu-fed sows were observed in total pigs born, piglet birth weight, litter weaning weights, pig weaning weight, and days to estrus postweaning; to actually observe benefits (rather than detriment) from this supplementation over a period exceeding 2 years in sows that completed the study is perhaps explained by the fact that in limit-fed sows, supply of a nutrient per unit body weight is much less than that of a common level in growing pigs given ad libitum access to feed. Improved weight gain of suckling pigs was also observed by Lillie and Frobish (1978), but other studies in which Cu was fed during late gestation and lactation (Thacker, 1991) or during lactation (Roos and Easter, 1986; Dove, 1993b) showed no response to added Cu in weight gain of suckling pigs.

The mechanisms whereby beneficial effects are observed from higher than routine supplementation levels of Cu are unknown. The growth-stimulating action of dietary Cu has been attributed to its antimicrobial actions (Fuller et al., 1960); however, evidence supporting this hypothesis is lacking. A correlation between the availability of Cu and the growth-promoting action of Cu has been observed (Bowland et al., 1961; Cromwell et al., 1989b). Zhou et al. (1994b) reported that both body weight gain and serum mitogenic activity were stimulated in young pigs given intravenous injections of Cu histidinate every other day for 18 days. Because the gastrointestinal tract was bypassed in this study, these results suggest that Cu can act systemically to promote growth. Recent evidence (Zhu et al., 2011) suggests that 175-250 ppm Cu affected mRNA expression levels of appetite-regulating genes in the hypothalamus. Feeding 250 ppm Cu has also stimulated lipase and phospholipase A activities and led to an improvement of dietary fat digestibility in weaning pigs (Luo and Dove, 1996). While, high dietary levels of Cu increase fecal Cu excretion, Payne et al. (1988) reported that when manure from pigs fed 250 ppm Cu (which contained up to 1,550 ppm Cu) was applied to soils for 8 years, it did not decrease corn yield on three different types of soils, and plant tissue Cu concentrations remained within the normal range. Their Cu fraction data indicated that the applied Cu was not available to plants. Cabral et al. (1998) confirmed the failure of plant tissue to be affected by the Cu in pig manure, an effect that was unique from Fe, Mn, and Zn. The potential toxicity of the manure for animals grazed on crops upon which the waste is spread is a matter of debate (Prince et al., 1975; Suttle and Price, 1976) that may depend on the manure application rate.

Iodine

The majority of the iodine (I) in swine is present in the thyroid gland, where it exists as a component of mono-, di-, tri-, and tetraiodothyronine (thyroxine). These hormones are important in the regulation of metabolic rate. Hart and Steenbock (1918), Kalkus (1920), and Welch (1928) demonstrated that hypothyroidism existed in swine raised in the northwestern United States and the Great Lakes region because of iodine-deficient feedstuffs produced on low-iodine soil.

The dietary iodine requirement is not well established. The requirement is increased by goitrogens, which are present in certain feedstuffs, including rapeseed, linseed, lentils, peanuts, and soybeans (McCarrison, 1933; Underwood, 1977; Schone et al., 1997a,b, 2001). A level of 0.14 ppm of iodine in a corn–soybean meal diet is adequate to prevent thyroid hypertrophy in growing pigs (Cromwell et al., 1975). A level of 0.35 ppm of added iodine prevented iodine deficiency in sows (Andrews et al., 1948).

Calcium iodate, potassium iodate, and pentacalcium orthoperiodate are nutritionally available forms of iodine and are more stable in salt mixtures than are sodium iodide or potassium iodide (Kuhajek and Andelfinger, 1970). The incorporation of iodized salt (0.007% iodine), at a level of 0.2% of the diet, provides sufficient iodine (0.14 ppm) to meet the needs of growing pigs fed grain–soybean meal diets.

A severe iodine deficiency causes pigs to be stunted and lethargic and to have an enlarged thyroid (Beeson et al., 1947; Braude and Cotchin, 1949; Sihombing et al., 1974). Sows fed iodine-deficient, goitrogenic diets farrow weak or dead pigs that are hairless, show symptoms of myxedema, and have an enlarged, hemorrhagic thyroid (Hart and Steenbock, 1918; Slatter, 1955; Devilat and Skoknic, 1971).

A dietary iodine level of 800 ppm decreased growth, hemoglobin level, and liver iron (Fe) concentration in growing pigs (Newton and Clawson, 1974). During lactation and the last 30 days of gestation, as much as 1,500-2,500 ppm of iodine was not harmful to sows (Arrington et al., 1965).

Iron

Iron (Fe) is required as a component of hemoglobin in red blood cells. Iron also is found in muscle as myoglobin, in serum as transferrin, in the placenta as uteroferrin, in milk as lactoferrin, and in the liver as ferritin and hemosiderin (Zimmerman, 1980; Ducsay et al., 1984). It also plays an important role in the body as a component of several metabolic enzymes (Hill and Spears, 2001).

Pigs are born with about 50 mg of Fe, most of which is present as hemoglobin (Venn et al., 1947). A high level of Fe fed to sows during late gestation (Brady et al., 1978) or parenteral administration of iron dextran to sows in gestation (Rydberg et al., 1959; Pond et al., 1961; Ducsay et al., 1984) does not substantially increase placental transfer of Fe to fetuses. The suckling pig has to retain 7-16 mg of Fe daily, or 21 mg of Fe/kg of body weight gain to maintain adequate levels of hemoglobin and storage Fe (Venn et al., 1947; Braude et al., 1962). Sow's milk contains an average of only 1 mg of Fe per liter (Brady et al., 1978). Thus, pigs receiving only milk rapidly develop anemia (Hart et al., 1930; Venn et al., 1947). Feeding of high levels of various Fe compounds, including iron sulfate and iron chelates, to gestating and lactating sows does not increase the Fe content of milk to an extent that Fe deficiency can be prevented. These levels can, however, prevent Fe deficiency in suckling pigs that have access to the sow's feces (Chaney and Barnhart, 1963; Veum et al., 1965; Spruill et al., 1971; Brady et al., 1978; Sansom and Gleed, 1981; Gleed and Sansom, 1982).

Numerous studies have shown the effectiveness of a single intramuscular injection of 100-200 mg of Fe, in the form of iron dextran, iron dextrin, or gleptoferron given in the first 3 days of life (Barber et al., 1955b; McDonald et al., 1955; Maner et al., 1959; Rydberg et al., 1959; Ullrey et al., 1959; Zimmerman et al., 1959; Kernkamp et al., 1962; Pollmann et al., 1983). The intestinal mucosa of the newborn pig actively absorbs Fe (Furugouri and Kawabata, 1975, 1976, 1979). Oral administration of Fe from bioavailable inorganic or organic sources within the first few hours of life also will meet the Fe needs of the suckling pig. However, early administration, before gut closure to large molecules, is crucial (Harmon et al., 1974a; Thoren-Tolling, 1975). An excessive level (more than 200 mg) of injectable or oral Fe is to be avoided because unbound serum Fe encourages bacterial growth and results in increased susceptibility to infection and diarrhea (Weinberg, 1978; Klasing et al., 1980; Knight et al., 1983; Kadis et al., 1984).

The Fe requirement of young pigs fed milk or purified liquid diets is 50-150 mg/kg of milk solids (Matrone et al., 1960; Ullrey et al., 1960; Manners and McCrea, 1964; Harmon et al., 1967; Hitchcock et al., 1974). Miller et al. (1982) suggested a requirement of 100 mg of Fe/kg of milk solids for pigs raised in a conventional or germ-free environment. The Fe requirement of pigs fed a dry, casein-based diet is about 50% higher per unit of dry matter than for those fed a similar diet in liquid form (Hitchcock et al., 1974).

The postweaning dietary Fe requirement is reported to be about 80 ppm (Pickett et al., 1960) by some investigators but as high as 200 ppm by other authors (Rincker et al., 2005; Lee et al., 2008). In later growth and maturity, this requirement diminishes as the rate of increase in blood volume slows. Natural feed ingredients usually supply enough Fe to meet postweaning requirements. Feed-grade defluorinated phosphate and dicalcium phosphate, which contain from 0.6 to 1.0% Fe, also supply substantial amounts of Fe.

Availability of Fe from different sources varies greatly (Zimmerman, 1980). Ferrous sulfate, ferric chloride, ferric citrate, ferric choline citrate, and ferric ammonium citrate are effective in preventing Fe deficiency anemia (Harmon et al., 1967; Ammerman and Miller, 1972; Ullrey et al., 1973; Miller et al., 1981). Iron compounds with low solubility, such as ferric oxide, are ineffective (Ammerman and Miller, 1972). The biovailability of Fe in ferrous carbonate is lower and more variable than that of Fe in ferrous sulfate (Harmon et al., 1969; Ammerman et al., 1974). Iron from iron methionine and an iron-glycine chelate have been reported to be from 68 to 180% as bioavailable as that in iron sulfate (Lewis et al., 1995; Kegley et al., 2002; Feng et al., 2007, 2009). The Fe in defluorinated phosphate is about 65% as available to the pig as the Fe in ferrous sulfate (Kornegay, 1972a). Soybean meal contains 175-200 ppm of Fe, and the bioavailability of Fe in soybean meal has been estimated to be 38%, based on hemoglobin depletion–repletion assays in chicks (Biehl et al., 1997).

The hemoglobin concentration of blood is a reliable indicator of the pig's Fe status, and it is easy to determine. Hemoglobin levels of 10 g/dL of whole blood are considered adequate. A hemoglobin level of 8 g/dL suggests borderline anemia, and a level of 7 g/dL or less represents anemia (Zimmerman, 1980). The type of anemia resulting from Fe deficiency is hypochromic-microcytic anemia. Anemic pigs show evidence of poor growth, listlessness, rough hair coats, wrinkled skin, and paleness of mucous membranes. Fast-growing anemic pigs may die suddenly of anoxia. A characteristic sign is labored breathing after minimal activity or a spasmodic jerking of the diaphragm muscles, from which the term "thumps" arises. Necropsy findings include an enlarged and fatty liver; thin, watery blood; marked dilation of the heart; and an enlarged, firm spleen. Anemic pigs are more susceptible to infectious diseases (Osborne and Davis, 1968). While supplemental Fe can improve total red blood cells, hemoglobin concentration, and plasma and liver Fe status of pigs, indiscriminate supplementation is to be avoided because it might also be associated with increased diarrhea incidence and reductions in growth rate (Lee et al., 2008).

In 3- to 10-day-old pigs, the toxic oral dose of Fe from ferrous sulfate is approximately 600 mg/kg of body weight (Campbell, 1961). Clinical signs of toxicity are observed within 1 to 3 hours after Fe is fed (Nilsson, 1960; Arpi and Tollerz, 1965). Lannek et al. (1962) and Patterson et al. (1967, 1969) reported that injectable Fe (100 mg as iron dextran) is toxic to pigs from vitamin E-deficient dams. While Fe deficiency in pigs increases gene expression of duodenal metal transporters (DMT1 and ZIP14), supplementation with 500 ppm Fe from ferrous sulfate reduces expression of those same transporters (Hansen et al., 2009). A dietary level of 5,000 ppm of Fe produces rachitic lesions, which may be prevented by increasing the level of dietary P (O'Donovan et al., 1963; Furugouri, 1972).

Manganese

Manganese (Mn) functions as a component of several enzymes involved in carbohydrate, lipid, and protein metabolism. Manganese is an obligatory constituent of mitochondrial superoxide dismutase (SOD) and is essential for the synthesis of chondroitin sulfate, a component of mucopolysaccharides in the organic matrix of bone (Leach and Muenster, 1962).

The dietary requirements for Mn are not well established and apparently quite low (Johnson, 1944). Leibholz et al. (1962) reported that as little as 0.4 ppm of Mn is sufficient for young pigs. With Mn-depleted dams, however, the requirement for the neonates is 3-6 ppm (Kayongo-Male et al., 1975). A corn–soybean meal diet has to contain ample Mn for normal growth and bone formation in growing-finishing pigs (Svajgr et al., 1969).

Long-term feeding of a diet containing only 0.5 ppm of Mn results in abnormal skeletal growth, increased fat deposition, irregular or absent estrous cycles, resorbed fetuses, small, weak pigs at birth, and reduced milk production (Plumlee et al., 1956). The Mn status of the sow affects the Mn status of the neonates, because Mn readily crosses the placenta (Newland and Davis, 1961; Gamble et al., 1971). On the basis of Mn retention, Kirchgessner et al. (1981) estimated the Mn requirement of pregnant sows at 25 ppm. Total litter weight at birth was less for sows fed a low-Mn, basal corn–soybean meal diet (10 ppm Mn) than for sows fed the basal diet plus 84 ppm Mn (Rheaume and Chavaz, 1989). Colostrum and milk from sows fed supplemental Mn contained a higher concentration of Mn, but retention of Mn was only numerically higher. Christianson et al. (1989, 1990) reported that birth weight of pigs was greater when sows were fed 10 or 20 ppm Mn than when they were fed 5 ppm. Also, return to estrus was improved by feeding 20 ppm Mn.

Although the toxic level of Mn is not well defined, reduced feed intake and growth rates have been observed when pigs were fed 4,000 ppm of Mn (Leibholz et al., 1962). A dietary level of 2,000 ppm of Mn resulted in reduced hemoglobin levels (Matrone et al., 1959), and 500 ppm of Mn reduced growth rate and resulted in limb stiffness in growing pigs (Grummer et al., 1950).

Selenium

Selenium (Se) is a component of the enzyme glutathione peroxidase (Rotruck et al., 1973), which detoxifies lipid peroxides and provides protection of cellular and subcellular membranes against peroxide damage. Thus, the mutual sparing effect of Se and vitamin E stems from their shared antiperoxidant roles. High levels of vitamin E, however, do not completely eliminate the need for Se (Ewan et al., 1969; Bengtsson et al., 1978a,b; Hakkarainen et al., 1978). Selenium has been shown to have a function in thyroid metabolism, because iodothyronine 5′-deiodinase has been identified as a selenoprotein (Arthur, 1994).

The dietary requirement for Se ranges from 0.3 ppm for weanling pigs to 0.15 ppm for finishing pigs and sows (Groce et al., 1971, 1973a,b; Ku et al., 1973; Mahan et al., 1973; Ullrey, 1974; Young et al., 1976; Glienke and Ewan, 1977; Wilkinson et al., 1977a,b; Mahan and Moxon, 1978a,b, 1984; Piatkowski et al., 1979; Meyer et al., 1981; Lei et al., 1998). The requirement for Se is influenced by dietary P level (Lowry et al., 1985b) but not dietary Ca level (Lowry et al., 1985a). Several forms of Se, including Se-enriched yeast, sodium selenite, and sodium selenate, are effective in meeting the dietary requirement (Mahan and Magee, 1991; Suomi and Alaviuhkola, 1992; Mahan and Kim, 1996; Mahan and Parrett, 1996). The Se status of the dam influences reproductive performance and the Se status of suckling and weanling pigs (Van Vleet et al., 1973; Mahan et al., 1977; Piatkowski et al., 1979; Chavez, 1985; Ramisz et al., 1993). Total body retention of Se, as well as serum and tissue levels of Se in growing, finishing, and reproducing gilts and their suckling progeny, increased as the dietary level of Se increased (0.1-0.3 or 0.5 ppm); the amount of Se retained and stored was usually greater at the various Se levels when an Se-enriched yeast source was compared to sodium selenite (Mahan, 1995; Mahan and Kim, 1996; Mahan and Parrett, 1996; Mahan and Peters, 2004). In reproducing gilts, serum glutathione peroxidase activity was not improved beyond 0.1 ppm Se, and the increase in activity was similar for Se-enriched yeast and sodium selenite (Mahan and Kim, 1996). When the stillbirth rate is high, it can be reduced with supplemental Se, as selenite or yeast (Yoon and McMillan, 2006). In growing-finishing pigs, serum Se concentration and serum glutathione peroxidase activity reached a plateau at a dietary level of 0.1 ppm Se for Se-enriched yeast and sodium selenite, but the magnitude of the response was lower for the yeast than for the sodium selenite at lower levels of supplementation, which suggests that the Se-enriched yeast product was less biologically available than sodium selenite (Mahan and Parrett, 1996; Mahan et al., 1999a). About 50% of the Se in the Se-enriched yeast product was suggested to be selenomethionine, with the remainder in one of several seleno-amino acids or as their analogs (Mahan, 1995). Several studies have been conducted examining vitamin E and Se effects on various aspects of boar fertility (Marin-Guzman et al., 1997, 2000a,b; Jacyno et al., 2002; Kolodziej and Jacyno, 2005; Echeverria-Alonzo et al., 2009). Many aspects (tissue [serum, liver, and testis] GSH-Px activity and Se and α-tocopherol concentrations, testicular sperm reserves, number of Sertoli cells, secondary spermatocytes, total sperm number per ejaculate, sperm motility, percentage of normal spermatozoa, head abnormalities, and retention of cytoplasmic droplets) are positively affected by treatments in these studies. In general, the effects of Se supplementation are more pronounced than those of vitamin E.

Certain soils of the United States and Canada are low in Se. When diets consist exclusively of ingredients grown in such regions, Se will be deficient unless supplemental selenium is added (Grant et al., 1961; Trapp et al., 1970; Ewan, 1971; Groce et al., 1971; Sharp et al., 1972a,b; Ku et al., 1973; Mahan et al., 1973, 1974; Diehl et al., 1975; Doornenbal, 1975; Piper et al., 1975; Wilkinson et al., 1977b; Bengtsson et al., 1978b). However, even with the supplementation of Se, tissue Se content will be influenced more by the indigenous Se content of the ingredients grown on those soils (Mahan et al., 2005). Environmental stress may increase the incidence and degree of selenium deficiency (Michel et al., 1969; Mahan et al., 1975).

In 1974, the U.S. Food and Drug Administration (FDA) approved the addition of 0.1 ppm of Se to all swine diets. In 1982, the FDA approved the addition of 0.3 ppm of Se to diets for pigs up to 20 kg, because 0.1 ppm of added Se does not always prevent deficiency signs in weanling pigs (Mahan and Moxon, 1978b; Meyer et al., 1981). The current regulation allows up to 0.3 ppm of Se in the diet for all pigs (FDA, 1987a,b). As reviewed by Ullrey (1992), concerns about environmental pollution by Se have led to efforts to reduce the level to 0.1 ppm, but the level of 0.3 ppm has been maintained.

The primary biochemical change in Se deficiency is a decline in glutathione peroxidase activity (Thompson et al., 1976; Young et al., 1976; Fontaine and Valli, 1977). Hence, the level of glutathione peroxidase in plasma is a reliable index of the Se status of pigs (Chavez, 1979a,b; Wegger et al., 1980; Adkins and Ewan, 1984). Sudden death is a prominent feature of the Se deficiency syndrome (Ewan et al., 1969; Groce et al., 1971, 1973a,b). The gross necropsy lesions of Se deficiency are identical to those of vitamin E deficiency. These include massive hepatic necrosis (hepatosis dietetica); edema of the spiral colon, lungs, subcutaneous tissues, and submucosa of the stomach; bilateral paleness and dystrophy of the skeletal muscles (white muscle disease); mottling and dystrophy of the myocardium (mulberry heart disease); impaired reproduction; reduced milk production; and impaired immune response (Orstadius et al., 1959; Lindberg and Siren, 1963, 1965; Trapp et al., 1970; Sharp et al., 1972a,b; Ruth and Van Vleet, 1974; Ullrey, 1974; Fontaine et al., 1977a,b,c; Nielsen et al., 1979; Sheffy and Schultz, 1979; Peplowski et al., 1980; Spallholz, 1980; Larsen and Tollersrud, 1981; Simesen et al., 1982).

When fed to growing swine as sodium selenite, sodium selenate, selenomethionine, or seleniferous corn, Se does not produce toxicity at levels of less than 5 ppm. However, levels of 5 ppm (Mahan and Moxon, 1984; Kim and Mahan, 2001a,b) and greater (Wahlstrom et al., 1955; Trapp et al., 1970; Herigstad et al., 1973; Goehring et al., 1984a,b) produced toxicity with the selenite form producing more severe and rapid selenosis effects than the yeast source (Kim and Mahan, 2001a,b). Signs of toxicity include inappetance, hair loss, fatty infiltration of the liver, degenerative changes in the liver and kidney, edema, occasional separation of hoof and skin at the coronary band (Miller, 1938; Miller and Williams, 1940; Wahlstrom et al., 1955; Orstadius, 1960; Lindberg and Lannek, 1965; Herigstad et al., 1973), and symmetrical, focal areas of vacuolation and neuronal necrosis (Stowe and Herdt, 1992). Dietary arsenicals help to alleviate Se toxicity (Wahlstrom et al., 1955).

Zinc

Zinc (Zn) is a component of many metalloenzymes, including DNA and RNA synthetases and transferases, and many digestive enzymes, and is associated with the hormone, insulin. Hence, this element plays an important role in protein, carbohydrate, and lipid metabolism. Additionally, Zn is involved in transcription as Zn fingers, and intra- and intercellular signals to the nucleus. High doses of Zn stimulate feed intake via increased ghrelin secretion from the stomach (Yin et al., 2009), have been reported (Hedemann et al., 2006) to increase the activity of several pancreatic enzymes, and increase the mucin staining area in the large intestine, and may change the epithelial morphology of the small intestine (Li et al., 2001).

Many diet-related factors influence the dietary requirement for Zn (Miller et al., 1979), including phytic acid or plant phytates (Oberleas et al., 1962; Oberleas, 1983), calcium (Tucker and Salmon, 1955; Hoekstra et al., 1956; Lewis et al., 1956, 1957a,b; Luecke et al., 1956, 1957; Stevenson and Earle, 1956; Bellis and Philp, 1957; Newland et al., 1958; Whiting and Bezeau, 1958; Berry et al., 1961; Hansard and Itoh, 1968; Morgan et al., 1969; Norrdin et al., 1973; Oberleas, 1983), Cu (Hoefer et al., 1960; O'Hara et al., 1960; Ritchie et al., 1963; Kirchgessner and Grassman, 1970), Cd (Pond et al., 1966), Co (Hoekstra, 1970), ethylenediamine tetraacetic acid (EDTA) (Owen et al., 1973), histidine (Dahmer et al., 1972a), and protein level and source (Smith et al., 1962; Dahmer et al., 1972b).

The Zn requirement of young pigs consuming a casein-glucose diet is low (15 ppm) because this diet does not contain factors such as phytate that reduce Zn availability (Smith et al., 1962; Shanklin et al., 1968). However, in pigs fed a conventional weanling diet, which would contain phytate, 80 ppm supplemental Zn was determined to be adequate (van Heugten et al., 2003). For growing pigs fed semipurified diets that contain isolated soybean protein or corn–soybean meal diets (both diets contain significant amounts of phytate) that contain the recommended level of Ca, the Zn requirement is about 50 ppm (Lewis et al., 1956, 1957a,b; Luecke et al., 1956; Stevenson and Earle, 1956; Smith et al., 1958, 1962; Miller et al., 1970). Boars have a higher Zn requirement than gilts, and gilts have a higher requirement than barrows (Liptrap et al., 1970; Miller et al., 1970). The Zn requirement is increased when excessive levels of Ca are fed (Lewis et al., 1956; Forbes, 1960; Hoefer et al., 1960; Pond and Jones, 1964; Pond et al., 1964; Oberleas, 1983). The Zn requirement of breeding animals is not well established, but may be higher than for growing pigs due to fetal growth, milk synthesis, tissue repair during uterine involution, and sperm production in boars. A level of 33 ppm of Zn in a corn–soybean meal diet for sows through five parities was adequate for optimal gestation performance, but not for lactation (Hedges et al., 1976). Kirchgessner et al. (1981) estimated the Zn requirement of pregnant sows at 25 ppm in a balance study. However, Payne et al. (2006) demonstrated an increase in pigs weaned/litter when a basal diet containing 100 ppm Zn from Zn sulfate was further supplemented with 100 ppm Zn from an organic source.

The classic sign of Zn deficiency in growing pigs is hyperkeratinization of the skin, a condition called parakeratosis (Kernkamp and Ferrin, 1953; Tucker and Salmon, 1955). Zinc deficiency reduces the rate and efficiency of growth and levels of serum Zn, alkaline phosphatase, and albumin (Hoekstra et al., 1956, 1967; Luecke et al., 1957; Theuer and Hoekstra, 1966; Miller et al., 1968, 1970; Prasad et al., 1969, 1971; Ku et al., 1970). A low level of dietary Zn (13 ppm) during the last 4 weeks of pregnancy prolongs the duration of farrowing (Kalinowski and Chavez, 1984). Gilts fed Zn-deficient diets during gestation and lactation produce fewer and smaller pigs, which have reduced serum and tissue Zn levels (Pond and Jones, 1964; Hoekstra et al., 1967; Hill et al., 1983a,c,d). The Zn concentration in milk from these dams is also reduced (Pond and Jones, 1964). Zinc deficiency retards testicular development, depletes seminiferous epithelium, and alters morphology of Sertoli cells of boars and thymic development of young pigs (Miller et al., 1968; Liptrap et al., 1970; Cigankova et al., 2008).

Bioavailabilities of Zn from zinc salts vary when these are included in the diet and can be influenced by the type of dietary ingredients used (Miller, 1991). The Zn in zinc sulfate, zinc carbonate, zinc chloride, and zinc metal dust is highly available (100%). Bioavailability estimates are expressed as a percentage of a recognized standard and do not refer to percentage absorbed or retained. Absorbed and retained Zn as a percentage of intake is usually much less than 50% of the intake. Zinc is less available from zinc oxide (50-80%) and is poorly available from zinc sulfide (Miller, 1991). Zinc from organic complexes seems to have approximately equal bioavailability to the Zn in zinc sulfate (Hill et al., 1986; Hahn and Baker, 1993; Wedekind et al., 1994; Schell and Kornegay, 1996; Swinkels et al., 1996; Cheng et al., 1998).

Zinc from grains and plant protein has low availability (Miller, 1991), but the availability is enhanced by microbial phytase addition to the diet (Kornegay, 1996).

A report that reduced postweaning scouring and increased weight gain resulted when the starting diet was supplemented with 3,000 ppm of Zn from zinc oxide for 14 days (Poulsen, 1989) stimulated a great deal of interest in the pharmacological use of Zn. Several studies have confirmed this finding of an effect on scouring/diarrhea (Rutkowska-Pejsak et al., 1998; Heo et al., 2010) and others have shown improved weight gain even in the absence of scouring (Hahn and Baker, 1993; McCully et al., 1995; Hill et al., 1996; Case and Carlson, 2002; Hollis et al., 2005; Han and Thacker, 2009). Levels of Zn varied from 2,000 to 6,000 ppm and were fed for up to 5 weeks in some studies. A study (Ward et al., 1996) compared zinc oxide and zinc methionine; they reported that supplementing starter diets with 250 ppm Zn from zinc methionine gave equal improvements in performance to 2,000 ppm Zn from zinc oxide; other studies have also shown benefit similar to that of zinc oxide from other forms of Zn (Mavromichalis et al., 2001; Case and Carlson, 2002). Some studies, however, have failed to observe beneficial effects of pharmacological levels of Zn (Fryer et al., 1992; Tokach et al., 1992; Schell and Kornegay, 1996). In studies with both high dietary levels of Zn (3,000 ppm, as zinc oxide) and Cu (250 ppm, as Cu sulfate), both were efficacious individually in terms of growth promotion, but were not additive when they were added in combination to diets for weanling pigs (Smith et al., 1997; Hill et al., 2000). However, other reports of high Zn levels and high levels of Cu from available sources report the effects are additive (Perez et al., 2011a). Hill et al. (2001) reported that improvements in performance with high Zn levels could be additive to antibiotics.

Zinc toxicity in growing pigs fed a corn–soybean meal diet supplemented with 2,000-4,000 ppm Zn from zinc carbonate was manifested by lethargy, arthritis, hemorrhage in axillary spaces, gastritis, and death. However, a dietary Zn level of 1,000 ppm was not toxic (Brink et al., 1959). Growing pigs fed 2,000-4,000 ppm of Zn from zinc oxide did not show symptoms of Zn toxicity (Cox and Hale, 1962; Hsu et al., 1975; Hill et al., 1983c). However, pigs became lame and unthrifty within 2 months when they were fed a diet containing 1,000 ppm of Zn from zinc lactate (Grimmett et al., 1937). High dietary Ca reduces the severity of Zn toxicity (Hsu et al., 1975). A 5,000-ppm dietary level of Zn as zinc oxide through two parities reduced litter size and pig weight at weaning and caused osteochondrosis in sows (Hill and Miller, 1983; Hill et al., 1983a). Pigs from sows fed high levels of dietary Zn have reduced tissue levels of Cu and rapidly develop anemia when fed a low-Cu diet (Hill et al., 1983c,d). Thus, the toxicity of Zn depends upon the Zn source, dietary level, the duration of feeding, and the levels of other minerals in the diet. The maximum tolerable dietary level for swine has been set at 1,000 ppm with the exception of zinc oxide, which may be included at higher levels for several weeks (NRC, 2005).

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7

Vitamins

INTRODUCTION

The term "vitamin" describes an organic compound distinct from amino acids, carbohydrates, and lipids that is required in small concentrations for normal growth and reproduction. Some vitamins may not be required in the diet because they can be synthesized from other feed or metabolic constituents, or by microorganisms in the intestinal tract. Vitamins are generally classified as either fat-soluble or water-soluble. The fat-soluble vitamins include vitamins A, D, E, and K. The water-soluble vitamins include the B-vitamins (biotin, choline, folacin, niacin, pantothenic acid, riboflavin, thiamin, B_6, and B_{12}) and vitamin C (ascorbic acid).

Vitamins are primarily required as coenzymes in nutrient metabolism. In feedstuffs, vitamins exist primarily as precursor compounds or coenzymes that may be bound or complexed in some manner. Hence, digestive processes are required to either release or convert vitamin precursors or complexes to usable and absorbable forms. The requirements for the individual vitamins at various stages of the life cycle are shown in tables provided in Chapter 16. To meet the deficiencies of vitamins in practical diets, vitamin premixes have been developed and are commonly added to swine diets. The amounts of vitamins in the premix (considering the inclusion rate in the final diet) may be substantially higher than the requirement estimates for the class of pig being fed because premixes lose vitamin potency depending on the length and manner of storage of the premix. Individual vitamins have varying degrees of sensitivity to a variety of factors such as moisture/humidity, light, heat, pH, and oxidizing agents. Additionally, feed processing practices such as extrusion or pelleting can further exacerbate vitamin losses prior to the actual consumption of the diet by the pig. Shurson et al. (2011) examined losses over a 120-day storage period and observed marked differences in vitamin loss among the vitamins as well as noting that in a combination vitamin-trace mineral premix, the stability was improved when metal-specific amino acid complexes were used as a source of trace mineral compared to inorganic sources.

Dietary addition of excess amounts of vitamins A and D to the diet has been demonstrated to have toxic effects in swine (Crenshaw, 2000; Darroch, 2000). In contrast, very few toxicity signs have been reported for the B-vitamins or for vitamins E and K (NRC, 1987; Crenshaw, 2000; Dove and Cook, 2000; Mahan, 2000).

Several studies have suggested that amounts of one or more of the commonly supplemented B-vitamins (riboflavin, niacin, pantothenic acid, and vitamin B_{12}) are inadequate for maximal performance of pigs (Lindemann et al., 1999; Stahly et al., 2007), whereas other studies do not support that concept (Mahan et al., 2007). Indeed, additions of these B-vitamins at amounts of 2 to 10 times the estimated requirements have tended to improve growth rate or feed efficiency of pigs. However, it is not known what level (above those suggested by the National Research Council [NRC] in 1988 and 1998) may be needed. Lindemann et al. (1995) observed a trend toward improved weight gain and feed intake in weanling pigs fed five times NRC (1988) levels of commonly supplemented vitamins (including fat-soluble vitamins), but feed efficiency tended to be poorer with the higher amounts of vitamin fortification. Although current pig genotypes differ from those used in the past and modern diets are often more energy dense than historical diets (which would affect feed intake and, thus, needed nutrient concentration in the diet), the fact that in the previously mentioned studies combinations of vitamins were added makes it impossible to establish revised estimates of requirements for individual B-vitamins. However, these studies certainly generate interest in supplementation beyond current NRC requirement estimates and illustrate the need for more research studies with individual vitamins.

Research in commercial settings has also generated some interesting observations relative to vitamin need. Coelho and Cousins (1997) reported on a study involving weanling to finishing pigs that grew out of a survey of supplementation rates for 23 entities in the swine industry. The survey illustrated that the lowest quartile of supplementation rates exceeded the amount needed to meet NRC (1988) requirement estimates, after accounting for expected contributions of bioavailable vitamins in the feed ingredients, by at least 2- to 15-fold for all growth stages, including at times supplementing vitamins that would not have been needed above those naturally supplied by the ingredients. Supplementation rates for the highest quartile were often 2- to 10-fold that of the lowest quartile. The performance study involved feeding pigs at the expected need to meet the NRC requirement estimate or at the lowest quartile, average, highest quartile, or highest 5% of the industry supplementation rate in conjunction with a stress factor that mimicked some of the stresses encountered in normal swine production. The stress factor was a low, medium, or high stress based on stocking density/floor space allowance, *E. coli* challenge, *Salmonella* challenge, mycotoxin challenge, and nutritional density of the diet. As expected, with increasing stress there was a reduction in growth rate and feed efficiency and an increase in mortality. In the low-stress conditions, there were no significant effects of increased vitamin fortification amounts on those response measures. However, in high-stress situations there were significant effects on all performance measures—growth rate, feed efficiency, and mortality—associated with increased supplementation. This type of study obviously confounds a variety of vitamins and a variety of stressors and cannot be used for establishing an individual vitamin need. However, it illustrates the difference in need that may exist between a commercial setting and a research setting that has to be reflected when extending requirement estimates into commercial settings.

The potential benefit of additional supplementation in reproducing sows was reported by Boyd et al. (2008). With breeding herds composed of sows of all parities, the situation exists where very large sows (which are limit fed in gestation to limit energy intake to avoid excessive growth) receive less vitamins and minerals per unit of body weight per day. Investigators observed that limitations of energy intake limit intake of all nutrients and that the largest sow had the least supply per unit body weight. The investigators introduced a treatment that elevated both vitamin and trace mineral intake that was equivalent (on a unit body weight basis) to increasing a sow having completed six parities to that of a sow having completed three parities. The results, when applied for one year of production and more than 50,000 litters, were that litter size was increased for sows in parities 4-10 on the increased premix concentration treatment (mean of 0.60 pigs weaned/litter or 1.44 pigs/sow per year), thereby partially blunting the normal decline in prolificacy associated with advancing parity. Again, while this type of study cannot be used for establishing an individual vitamin need, it illustrates potential situation-specific needs that may not be addressed in the research contributing to requirement estimates, as well as the potential need to express breeding animal requirements in a different manner when extending requirement estimates into commercial settings.

With regard to potential need in reproducing boars, Audet et al. (2004) examined supra-supplementation of vitamin C (1,000 mg/kg of diet), water-soluble vitamins (10 × the industry average from a commercial survey), or fat-soluble vitamins (3-5 × the industry average) beyond that normally supplemented to determine the potential benefit on vitamin status, libido, and semen characteristics in young boars under normal and intensive semen collection. During the intensive collection period, greater semen production was observed in boars supplemented with the water-soluble vitamins. During the recovery period, the percentage of motile sperm cells was also greater in these boars. Both of these responses were observed, but to a lesser extent, in boars supplemented with the fat-soluble vitamins compared with control boars. Sperm morphology and libido were not affected by treatments. Thus, greater dietary supplementation of water-soluble and fat-soluble vitamins may increase semen production during intensive semen collection but whether all vitamins or only a single vitamin in each treatment group needs to be increased cannot be determined based on the treatments utilized. There were no benefits observed from the vitamin C supplementation. In a follow-up study utilizing the same vitamin supplementation levels but combining the water and fat-soluble vitamins in a single treatment (Audet et al., 2009), the vitamin supplement did not affect sperm production or sperm quality, although semen volume was increased during one of the collection periods for the supplemented boars.

FAT-SOLUBLE VITAMINS

Vitamin A

Vitamin A is essential for vision, reproduction, the growth and maintenance of differentiated epithelia, and mucus secretions (Wald, 1968; Goodman, 1979, 1980). Evidence also demonstrates that vitamin A is involved in gene transcription, embryonic development, bone metabolism, hematopoiesis, and aspects of immunity (Combs, 1999).

Vitamin A nomenclature policy (Anonymous, 1990) dictates that the term "vitamin A" be used for all β-ionone derivatives, other than provitamin A carotenoids, that exhibit the biological activity of all-trans retinol (i.e., vitamin A alcohol, or retinol). Vitamin A is present in animal tissues, eggs, and whole milk, whereas plant materials contain only provitamin A precursors that are acted upon in the gut or by the liver to form retinol. Both natural vitamin A and synthetic retinol analogs are commonly referred to as retinoids. On the basis of rat data, 1 IU of vitamin A equals 0.3 µg of crystalline vitamin A alcohol, 0.344 µg of vitamin A acetate, or 0.55 µg of vitamin A palmitate. Retinol equivalent (RE) is the currently accepted nomenclature used to describe the vitamin activity in foods and feeds. One RE is defined as 1 μg of all-trans retinol.

Pigs are less efficient than poultry or rats in converting carotenoid precursors to vitamin A. This conversion occurs primarily in intestinal mucosa (Fidge et al., 1969). Active carotenoid pigments in corn–soybean meal diets (Wellenreiter et al., 1969) and their bioactivities relative to all-trans β-carotene (100%) are β-zeacarotene (25%) and cryptoxanthin (57%), as estimated by Petzold et al. (1959), Duel et al. (1945), and Greenberg et al. (1950). Ullrey (1972) calculated, therefore, that the all-trans β-carotene equivalent would be only 52% of the chemically determined carotene value. He then calculated that this value for swine would be only 16%, based on the fact that pigs are only 30% as efficient as rats in converting β-carotene in swine diets to usable vitamin A (Braude et al., 1941). When this value is multiplied by 1,667 IU, which represents the theoretical vitamin A potency of 1 mg of all-trans β-carotene for rats, 1 mg of chemically determined carotene in a corn–soybean meal pig diet would have a calculated potency of 267 IU, or 80 μg of vitamin A alcohol.

Chew et al. (1982) and Brief and Chew (1985) have suggested that β-carotene plays a role in reproduction that is independent of vitamin A. Their studies involving β-carotene injection suggest that elevation of maternal plasma vitamin A or β-carotene may improve embryonic survival, possibly because more uterine-specific proteins are secreted. Dietary addition of β-carotene did not elicit a response. This failure is probably due to the poor absorption of intact β-carotene in the pig (Poor et al., 1987). Swine are able to store vitamin A in the liver, which makes the vitamin available during periods of low intake. Requirements for vitamin A depend on the criteria evaluated; weight gain is less sensitive than cerebrospinal fluid pressure, liver storage, or plasma levels. For pigs during the first 8 weeks of life, 75 to 605 μg of retinyl acetate/kg of diet is required, depending on the response criteria used (Sheffy et al., 1954; Frape et al., 1959). With growing-finishing pigs, the requirement varies from 35 to 130 μg/kg, when daily gain is used as the criterion, and from 344 to 930 μg/kg, when liver storage and cerebrospinal fluid pressure are used as the criteria (Guilbert et al., 1937; Braude et al., 1941; Hentges et al., 1952; Myers et al., 1959; Hjarde et al., 1961; Nelson et al., 1962; Ullrey et al., 1965). The presence of nitrite or nitrate in feed or water can increase the vitamin A requirement (Seerley et al., 1965; Wood et al., 1967; Hutagalung et al., 1968).

The vitamin A reserves of the sow make it difficult to establish requirements. Braude et al. (1941) reported that mature sows fed diets without supplemental vitamin A completed three pregnancies normally; only in the fourth pregnancy did signs of vitamin deficiency appear. Gilts receiving adequate vitamin A amounts until 9 months of age, followed by a diet containing no vitamin A, completed two reproductive cycles without signs of vitamin A deficiencies (Hjarde et al., 1961; Selke et al., 1967). Heaney et al. (1963) fed depleted gilts 16, 5, or 2.5 μg of retinyl palmitate/kg body weight daily with no effects on litter size, birth weight, or survival rate. Parrish et al. (1951) suggested that 2,100 IU of vitamin A/day during gestation and lactation was adequate to maintain normal serum and liver concentrations. Recently, in a multistation study involving sows of various genetic backgrounds, Lindemann et al. (2008) demonstrated that intramuscular injection of high doses (250,000 or 500,000 IU of vitamin A) in young sows (parity 1 and 2) at weaning and breeding increased linearly the subsequent number of pigs born and weaned per litter, whereas for sows of parity 3 to 6, litter sizes were not affected by the vitamin A treatments. The injectable treatments were in addition to a basal diet that contained 11,000 IU vitamin A/kg of diet. Thus, the vitamin A requirement for maximal performance may vary with age, and the requirement may not be able to be met simply with dietary supplementation.

Vitamin A deficiency in swine results in reduced weight gain, incoordination, posterior paralysis, blindness, increased cerebrospinal fluid pressure, decreased plasma levels, and reduced liver storage (Guilbert et al., 1937; Braude et al., 1941; Hentges et al., 1952; Frape et al., 1959; Hjarde et al., 1961; Nelson et al., 1962, 1964).

Gross toxicity signs of hypervitaminosis A include a roughened hair coat, scaly skin, hyperirritability and sensitivity to touch, bleeding from cracks that appear in the skin about the hooves, blood in urine and feces, loss of control of the legs accompanied by inability to rise, and periodic tremors (Anderson et al., 1966). Young pigs fed diets containing 605,000, 484,000, 363,000, or 242,000 μg of retinyl palmitate/kg of diet developed signs of vitamin A toxicity in 16, 17.5, 32, and 43 days, respectively. No signs of toxicity were observed when pigs were fed 121,000 μg of added retinyl palmitate/kg of diet for 8 weeks (Anderson et al., 1966). Wolke et al. (1968) observed lesions in endochondral and intramembranous bone within 5 weeks when pigs were fed these excessive amounts of vitamin A. The NRC (1987) has determined the presumed upper safe levels for growing and breeding swine to be 20,000 and 40,000 IU/kg of diet, respectively.

Vitamin A esters are more stable in feeds and premixes than is retinol. The hydroxyl group as well as the four double bonds on the retinol side chain are subject to oxidative losses. Thus, esterification of vitamin A alcohol does not totally protect this vitamin from oxidative losses. Current commercial sources of vitamin A are generally "coated" esters (1 IU of vitamin A = 0.344 μg of retinyl acetate, or 0.549 μg of retinyl palmitate) that contain an added antioxidant such as ethoxyquin or butylated hydroxytoluene (BHT).

Moisture in premixes and feedstuffs has a negative effect on vitamin A stability (Baker, 1995). Water causes vitamin A beadlets to soften and become more permeable to oxygen. Thus, both high humidity and presence of free choline chloride (which is very hygroscopic) enhance vitamin A destruction. Trace minerals also exacerbate vitamin A losses in premixes exposed to moisture. For maximum retention of vitamin A activity, premixes have to be as moisture-free as possible and have a pH above 5. Low pH causes isomerization of all-trans vitamin A to less potent cis forms and also results in deesterification of vitamin A esters to more labile retinol (De Ritter, 1976).

Vitamin D

The two major forms of vitamin D are ergocalciferol (vitamin D_2) and cholecalciferol (vitamin D_3). The action of ultraviolet light on the ergosterol that is present in plants forms ergocalciferol; the photochemical conversion of 7-dehydrocholesterol in the skin of animals forms cholecalciferol. One IU of vitamin D is defined as the biological activity of 0.025 µg of cholecalciferol. Ergocalciferol and cholecalciferol are hydroxylated in the liver to the 25-hydroxy forms. The 25-hydroxy-D_3 is further hydroxylated in the kidney to either 1,25-dihydroxy-D_3 or 24,25-dihydroxy-D_3. Several mechanisms that act according to established criteria for hormones control the synthesis and reactions of the dihydroxylated metabolites; therefore, the dihydroxylated D_3 metabolites are viewed as hormones (Schnoes and DeLuca, 1980; Kormann and Weiser, 1984).

Vitamin D and its hormonal metabolites act on the mucosal cells of the small intestine, causing the formation of calcium-binding proteins. These proteins facilitate calcium, magnesium, and phosphorus absorption. The actions of vitamin D metabolites, together with parathyroid hormone and calcitonin, maintain calcium and phosphorus homeostasis. Braidman and Anderson (1985) have reviewed the endocrine functions of vitamin D.

Bethke et al. (1946) indicated that vitamins D_2 and D_3 were equally effective in meeting the vitamin D needs of swine. Horst et al. (1982), however, demonstrated that pigs discriminate in their metabolism of the two forms of vitamin D. Additional research is needed in swine to quantify the differences in absorption and utilization of these forms.

The vitamin D_2 requirement of the baby pig fed a casein-glucose diet is 100 IU/kg of diet (Miller et al., 1964, 1965). The requirement is higher if isolated soy protein is fed (Miller et al., 1965; Hendricks et al., 1967). Vitamin D deficiency reduces retention of calcium, phosphorus, and magnesium (Miller et al., 1965). Bethke et al. (1946) suggested a minimum requirement of 200 IU/kg of diet for growing pigs. In other studies, however, vitamin D supplementation did not improve weight gain (Wahlstrom and Stolte, 1958; Combs et al., 1966).

Weisman et al. (1976), Boass et al. (1977), Noff and Edelstein (1978), Halloran and DeLuca (1979), and Pike et al. (1979) showed that vitamin D is involved in rat reproduction and lactation. Parenteral cholecalciferol treatment of sows before parturition provided an effective means of supplementing pigs with cholecalciferol (via the sow's milk) and its dihydroxy metabolites by placental transport (Goff et al., 1984). Lauridsen et al. (2010) compared four levels of supplementation of either D_3 or a newly developed vitamin D product (25-hydroxycholecalciferol) at four concentrations (200, 800, 1,400, and 2,000 IU/kg of vitamin D) of the two forms. Reproductive performance for one parity was influenced little by dietary vitamin D treatments. A decreased number of stillborn pigs with the higher doses of vitamin D (1,400 and 2,000 IU of vitamin D, resulting in 1.17 and 1.13 stillborn pigs per litter, respectively) compared with the lower doses of vitamin D (200 and 800 IU of vitamin D, resulting in 1.98 and 1.99 stillborn pigs per litter, respectively) was observed, but numbers of live pigs at birth and at weaning were not affected. In a concurrent study with gilts fed during the first 28 days of gestation, the ultimate strength of the bones and their content of ash were greater when vitamin D_3 was supplemented compared with the same amount of 25-hydroxycholecalciferol and results were maximized at 800 IU. The authors recommended a dietary dose of approximately 1,400 IU of vitamin D for reproducing swine.

Vitamin D deficiency causes disturbances in the absorption and metabolism of calcium and phosphorus that result in insufficient bone calcification. In young growing pigs, vitamin D deficiency results in rickets, whereas in mature swine a deficiency causes diminished bone mineral content (osteomalacia). In severe vitamin D deficiency, pigs may exhibit signs of calcium and magnesium deficiency, including tetany. It takes 4 to 6 months for pigs fed a vitamin D-deficient diet to develop signs of a deficiency (Johnson and Palmer, 1939; Quarterman et al., 1964). While perturbations in Ca metabolism and bone development are a primary effect of vitamin D deficiency, vitamin D is involved in many more physiological functions. It is also necessary for the growth and health of soft tissue; receptors for 1,25-$(OH)_2D_3$ have been found in 33 organs of mammals (Zempleni et al., 2007), and it is known to have a role in immunity, endocrine function, neurological function, and reproduction. Viganò et al. (2003) suggested that vitamin D may be essential for normal implantation and placentation. In 1999, the Institute of Medicine (IOM, 1999) proposed that the concentration of 25-$(OH)D_3$ be used as an index of vitamin D status in humans. Vitamin D deficiency was suggested to be reflected in plasma concentrations of less than 25 nmol/L. Borderline deficiency was suggested to be up to 50 nmol/L of 25-$(OH)D_3$ in plasma (Mosekilde, 2005). If these cutoff values ultimately are demonstrated to be applicable in swine, sows fed vitamin D concentrations less than 1,400 IU/kg and sows especially in the first 2 weeks of lactation may be deemed deficient.

Vitamin D toxicity was produced in weanling pigs supplemented with a daily oral dose of 6,250 µg of vitamin D_3 for 4 weeks (Quarterman et al., 1964). This level of D_3 reduced feed intake; growth rate; and weights of the liver, radius, and ulna. At necropsy, calcification was observed in the aorta, heart, kidney, and lung. Feeding a daily amount of 11,825 µg of vitamin D_3 to pigs weighing 20 to 25 kg resulted in death in 4 days (Long, 1984). Vitamin D_3 has been shown to be more toxic than vitamin D_2 in a number of species, including swine (NRC, 1987). The development of methods to measure vitamin D and its metabolites in plasma has provided insights regarding the possible mechanisms that cause differences in toxicity between vitamins D_2 and D_3 (Horst et al., 1981; NRC, 1987). For growing swine, the presumed maximal safe level of vitamin D_3 for long-term feeding conditions (more than 60 days) is 2,200 IU D_3/kg of diet. Under short-term feeding conditions (less than 60 days), swine can tolerate as much as 33,000 IU D_3/kg of diet (NRC, 1987).

Vitamin E

There are eight naturally occurring forms of vitamin E: α, β, γ, and δ tocopherols (Evans et al., 1936; Emerson et al., 1937; Stern et al., 1947) and α, β, γ, and δ tocotrienols (Green et al., 1960; Pennock et al., 1964; Whittle et al., 1966). Of these, D-α-tocopherol possesses the greatest biological activity (Brubacher and Wiss, 1972; Ames, 1979; Bieri and McKenna, 1981). One IU of vitamin E is the activity of 1 mg of DL-α-tocopheryl acetate. The D isomer is more bioactive than the L isomer. On the basis principally of rat bioassay work and using DL-α-tocopheryl acetate as a standard (1 mg = 1 IU), it has historically been calculated that 1 mg DL-α-tocopherol equals 1.1 IU, 1 mg D-α-tocopheryl acetate equals 1.36 IU, and 1 mg D-α-tocopherol equals 1.49 IU of vitamin E. For young pigs, Chung et al. (1992) reported that 1 mg D-α-tocopherol equals 2.44 IU. Anderson et al. (1995a), however, suggested that D-α-tocopheryl acetate is utilized more efficiently by pigs than by rats. Also with young pigs, Wilburn et al. (2008) demonstrated that natural vitamin E (*RRR*-α-tocopheryl acetate) was a superior source compared with synthetic vitamin E (all-rac-α-tocopheryl acetate) suggesting that the bioequivalence values underestimate the value of the natural source of vitamin E in pigs. And work with sows (Mahan et al., 2000) and finishing pigs (Yang et al., 2009) demonstrated that when supplemental vitamin E sources were provided on an equivalent IU basis, the results suggested that D-α-tocopheryl acetate has a higher equivalency than DL-α-tocopheryl acetate. Lauridsen et al. (2002), using deuterium-labeled vitamin E administered to sows, demonstrated that swine discriminate between *RRR*- and all-rac-α-tocopherols, which resulted in an approximately twofold higher plasma α-tocopherol concentration arising from the *RRR* form. The 2:1 ratio of *RRR* to all-rac in pigs is higher than the currently accepted USP definition of *RRR*:all-rac of 1.36:1.00 and is, perhaps, a preferred ratio. While the bioequivalence values for vitamin E derived from the natural source compared to the synthetic source are greater in pigs than were determined in rats, it has also been considered, as Dove and Ewan (1991) demonstrated, that the rate of oxidation of natural tocopherols is increased in diets containing increased amounts of Cu, Fe, Zn, or Mn.

For many years the primary source of vitamin E in feed was the tocopherols found in green plants and seeds. Oxidation, which is accelerated by heat, moisture, rancid fat, and trace minerals, rapidly destroys natural vitamin E. Therefore, predicting the amount of vitamin E activity in feed ingredients is difficult. Vitamin E losses of 50 to 70% can occur in alfalfa stored at 32°C for 12 weeks; losses of 5 to 30% can occur during dehydration of alfalfa (Livingston et al., 1968). Storage of high-moisture grain or its treatment with organic acids greatly reduces its vitamin E content (Madsen et al., 1973; Lynch et al., 1975; Young et al., 1975, 1978). High amounts of dietary vitamin A have also been reported to lower vitamin E absorption (Hoppe et al., 1992), although Anderson et al. (1995b) observed no effects on vitamin E status when growing pigs were fed diets containing 15 times the vitamin A requirement.

During the 1970s, many studies on the vitamin E requirement of swine were conducted. The Agricultural Research Council (1981) and Ullrey (1981) have reviewed the studies. Many dietary factors affect the vitamin E requirement, including amounts of selenium, unsaturated fatty acids, sulfur amino acids, retinol, copper, iron, and synthetic antioxidants. Michel et al. (1969) prevented deaths in pigs fed a corn–soybean diet containing 5 to 8 mg of vitamin E/kg and 0.04 to 0.06 mg of selenium/kg by supplementing the diet with 22 mg of vitamin E/kg. Studies with corn–soybean meal diets fed to growing-finishing pigs suggest that 5 mg of vitamin E/kg and 0.04 mg of selenium/kg are inadequate for growing-finishing pigs and may result in deficiency lesions and mortality. In the presence of adequate selenium, however, supplements of 10 to 15 mg of vitamin E/kg of diet prevented mortality and deficiency lesions and supported normal performance (Groce et al., 1971, 1973; Sharp et al., 1972a,b; Ullrey, 1974; Wilkinson et al., 1977b; Hitchcock et al., 1978; Mahan and Moxon, 1978; Meyer et al., 1981). The amount of vitamin E necessary to prevent deficiency signs varies considerably because of variation in dietary amounts of selenium (Agricultural Research Council, 1981; Ullrey, 1981), antioxidants (Tollerz, 1973; Simesen et al., 1982), and lipids (Nielsen et al., 1973; Tiege et al., 1977, 1978).

Inclusion of high amounts of vitamin E in the diet may increase the immune response (Ellis and Vorhies, 1976; Tiege, 1977; Nockels, 1979; Peplowski et al., 1980; Wuryastuti et al., 1993), although Bonnette et al. (1990) found no evidence of an increased humoral or cell-mediated immune response in young pigs fed high amounts of vitamin E. Pinelli-Saavedra et al. (2008) observed that the supplementation of sows with both 500 mg/kg of feed of α-tocopherol acetate and 10 g/day of vitamin C (ascorbic acid) throughout gestation and lactation to a diet already supplemented with 36 IU vitamin E/kg significantly increased the total immunoglobulin and immunoglobulin G (IgG) concentrations in pigs at day 21 of lactation (neither vitamin alone elicited an increased response. A synergism between vitamin E and Se was observed by Mavromatis et al. (1999) when they imposed an additional 30 mg of α-tocopherol/kg of diet and/or three intramuscular Se injections of 30 mg, on days 30, 60, and 90 of pregnancy to sows fed a diet that was supplemented with α-tocopherol and Se content of 20 mg/kg and 0.45 mg/kg, respectively. The additional vitamin E increased serum IgG in sows at farrowing and in pigs at 24 hours postpartum and at day 28; the combined treatment enhanced serum IgG values further.

Vitamin E functions as an antioxidant at the cell membrane level, and it has a structural role in cell membranes. There are vitamin E deficiency diseases that respond to vitamin E, selenium, or antioxidants. Vitamin E deficiency results in a wide variety of pathological conditions. These include skeletal and cardiac muscle degeneration, degenerative thrombotic vessel injury, gastric parakeratosis, gastric ulcers, anemia, liver necrosis, yellow discoloration of fat tissue, and sudden death (Obel, 1953; Davis and Gorham, 1954; Hove and Seibold, 1955; Dodd and Newling, 1960; Grant, 1961; Lannek et al., 1961; Nafstad, 1965, 1973; Nafstad and Nafstad, 1968; Reid et al., 1968; Ewan et al., 1969; Michel et al., 1969; Nafstad and Tollersrud, 1970; Trapp et al., 1970; Baustad and Nafstad, 1972; Sharp et al., 1972a,b; Sweeney and Brown, 1972; Wastell et al., 1972; Piper et al., 1975; Bengtsson et al., 1978a,b; Hakkarainen et al., 1978; Tiege and Nafstad, 1978; Simesen et al., 1982). In addition, vitamin E may be involved in the mastitis-metritis-agalactia (MMA) complex of sows (Ringarp, 1960; Ullrey et al., 1971; Whitehair et al., 1984).

Information is available on the vitamin E requirements for reproduction (Hanson and Hathaway, 1948; Adamstone et al., 1949; Cline et al., 1974; Malm et al., 1976; Young et al., 1977, 1978; Wilkinson et al., 1977a; Nielsen et al., 1979; Piatkowski et al., 1979; Mahan, 1991, 1994). Placental transfer of tocopherol from dam to fetus is minimal, so the offspring have to rely on colostrum and milk to meet their daily needs (Pinelli-Saavedraa and Scaifeb, 2005). The content of vitamin E in sow colostrum and milk is dependent on the vitamin E content of the sow's diet (Mahan, 1991). In many studies, diets containing 5 to 7 mg/kg of vitamin E and 0.1 mg/kg of inorganic selenium have prevented deficiency lesions and supported normal reproductive performance. However, the addition of 0.1 mg/kg of inorganic selenium and 22 mg/kg of vitamin E to diets appears necessary to maintain tissue vitamin E levels (Piatkowski et al., 1979). Additionally, research in the 1990s (Mahan, 1991, 1994; Wuryastuti et al., 1993) suggested that vitamin E levels as high as 44 to 60 mg/kg during gestation and lactation may be necessary to maximize both litter size and immunocompetence.

Several studies have been conducted examining vitamin E and Se effects on various aspects of boar fertility (Marin-Guzman et al., 1997; 2000a,b; Jacyno et al., 2002; Kolodziej and Jacyno, 2005; Echeverria-Alonzo et al., 2009). Many aspects (tissue [serum, liver, and testis] glutathione peroxidase activity and Se and α-tocopherol concentrations, testicular sperm reserves, number of Sertoli cells, secondary spermatocytes, total sperm number per ejaculate, sperm motility, percentage of normal spermatozoa, head abnormalities, and retention of cytoplasmic droplets) are positively affected by treatments in these studies. However, because of the feeding of unsupplemented control diets, the limited number of treatments, or a confounding of the two nutrients in the treatment structure, a level of supplementation to maximize boar fertility cannot be derived. In general, however, the effects of Se supplementation are more pronounced than those of vitamin E.

Vitamin E is generally considered to be one of the least toxic of the vitamins. Vitamin E toxicity has not been demonstrated in swine. Levels as high as 550 mg/kg of diet have been fed to growing pigs without toxic effects (Bonnette et al., 1990). Hypervitaminosis E has been studied in rats, chicks, and humans; these scant data indicate maximum tolerable levels to be in the range of 1,000 to 2,000 IU/kg of diet (NRC, 1987).

Vitamin K

Although it was the last of the four fat-soluble vitamins to be discovered, the metabolic role of vitamin K has been more clearly defined than that of vitamins A, D, or E (Suttie, 1980; Kormann and Weiser, 1984). Vitamin K is essential for the synthesis of prothrombin, factor VII, factor IX, and factor X, which are necessary for the normal clotting of blood. These proteins are synthesized in the liver as inactive precursors. The action of vitamin K converts them to biologically active compounds (Suttie and Jackson, 1977; Suttie, 1980). This activation occurs by enzymatic γ-carboxylation of specific glutamate residues. The resulting carboxyglutamate residues are strong chelators of calcium ions, which are essential for blood coagulation. A deficiency of vitamin K or the presence of anticoagulation compounds reduces the number of carboxyglutamate residues, resulting in a loss of activity and prolonged bleeding times. In addition to its role in blood clotting, there is evidence that vitamin K-dependent protein and peptides may be involved in calcium metabolism (Suttie, 1980; Kormann and Weiser, 1984).

Vitamin K exists in three series: the phylloquinones (K_1) in plants; the menaquinones (K_2), formed by microbial fermentation; and the menadiones (K_3), which are synthetic. Menadione (2-methyl-1,4-naphthoquinone) is the synthetic form of vitamin K, which has the same cyclic structure as vitamins K_1 and K_2. All three forms of vitamin K are biologically active.

Water-soluble forms of menadione are commonly used to supplement swine diets. The major forms are menadione sodium bisulfite (MSB) and menadione dimethylpyrimidinol bisulfite (MPB) and menadione sodium bisulfite complex (MSBC). The vitamin K activity depends upon the menadione content of these products: 50, 33, and 45% menadione in MSB, MSBC, and MPB, respectively. Menadione nicotinamide bisulfite is a synthetic form of vitamin K that has been shown to have both vitamin K and niacin bioactivity in chicks similar to that of MPB (Oduho et al., 1993) and it contains 46% menadione.

Vitamin K deficiency increases prothrombin and clotting times and may result in internal hemorrhages and death (Schendel and Johnson, 1962; Brooks et al., 1973; Seerley et al., 1976; Hall et al., 1986, 1991). Schendel and Johnson (1962) reported a requirement of 5 µg of menadione sodium phosphate/kg of body weight for 1- and 2-day-old pigs fed a purified liquid diet. Their diet contained sulfathiazole and oxytetracycline to reduce the intestinal synthesis of vitamin K. Wire-bottomed cages were used and carefully cleaned to minimize coprophagy. Seerley et al. (1976) reported that 1.1 mg of MPB/kg of diet counteracted the effects of the anticoagulant pivalyl (2-pivalyl-1,3-indandione) in weanling pigs. Hall et al. (1986) suggested that 2 mg/kg of menadione as MPB was needed to counteract the effects of pivalyl in growing pigs.

Bacterial synthesis of vitamin K and subsequent absorption following coprophagy may reduce or eliminate the need for supplemental vitamin K. High amounts of antibiotics may decrease the synthesis of vitamin K by the intestinal flora. Studies have not been conducted to determine whether a supplemental source of vitamin K is beneficial for the breeding herd.

Muhrer et al. (1970), Osweiler (1970), and Fritschen et al. (1971) reported an occurrence of hemorrhagic conditions in pigs under field conditions. Mycotoxin-contaminated ingredients were suspected in these incidents, and vitamin K supplementation (2.0 mg of menadione/kg of diet) prevented the hemorrhagic syndrome. In some of these studies, the presence of anticlotting coumarins may have increased the dietary requirement for vitamin K. Excess calcium may also increase the pig's requirement for vitamin K (Hall et al., 1991). Liver stores of vitamin K can be depleted very rapidly during even very short periods of vitamin K-deficient diet consumption (Kindberg and Suttie, 1989). The ubiquitous nature of mycotoxins (BIOMIN, 2010) and the use of coproducts in swine diets (in which mycotoxins can be concentrated [Schaafsma et al., 2009]) suggest that further vitamin K research may be beneficial to swine.

Stability of water-soluble menadione supplements in premixes and diets is impaired by moisture, choline chloride, trace elements, and alkaline conditions. Coelho (1991) suggested that MSBC and MPB can lose up to 80% of bioactivity if stored for 3 months in a vitamin–trace-mineral premix containing choline. Activity losses were far less when the menadione compounds were stored in the same premix that did not contain choline. Some menadione supplements are now coated, and this appears to improve stability in diets and premixes.

Even very large amounts of menadione compounds are tolerated well by animals. Seerley et al. (1976) fed 110 mg MPB/kg of diet to pigs, and Oduho et al. (1993) fed 300 mg MPB/kg of diet to chicks; neither observed signs of toxicity. A dietary amount of 3,000 mg of MPB/kg did not reduce weight gain or blood hemoglobin when fed over a 14-day period to chicks. It appears that menadione levels of 1,000 times an animal's requirement are well tolerated (NRC, 1987; Oduho et al., 1993).

WATER-SOLUBLE VITAMINS

Biotin

Biotin is important metabolically as a cofactor for several enzymes that function in carbon dioxide fixation. As part of pyruvate carboxylase and propionyl CoA carboxylase, it is important in gluconeogenesis and in the citric acid cycle. Acetyl CoA carboxylase is also a biotin-dependent enzyme that functions in initiating fatty acid biosynthesis. Whitehead et al. (1980) and Misir and Blair (1986) suggested that plasma biotin concentration and plasma pyruvate carboxylase activity are methods of assessing the biotin status of pigs. The D-isomer of biotin is the biologically active form of the vitamin.

Biotin is present in most common feedstuffs in more-than-adequate amounts, but its bioavailability varies greatly among ingredients. The bioavailability of biotin in yellow corn and soybean meal is high for the chick, but its bioavailability in barley, grain sorghum, oats, and wheat is lower (Frigg, 1976; Anderson et al., 1978; Kopinski et al., 1989). Much of the biotin in feed ingredients exists as ε-N-biotinyl L-lysine (biocytin), which is a component of protein. The bioavailability of biocytin (relative to crystalline D-biotin) varies widely and is dependent on the digestibility of the proteins in which it is found. A considerable portion of the pig's biotin requirement is presumed to come from bacterial synthesis in the gut.

In general, performance has not been improved by supplemental biotin in a wide range of diets and conditions for pigs weaned at 2 to 28 days of age or for growing-finishing pigs. Pigs from 2 to 28 days of age fed a filtered skim milk diet containing about 10 µg of biotin/kg of dry matter (about 15% of the level in sow's milk) gained weight and were as efficient in feed conversion as littermate pigs supplemented with 50 µg of biotin/kg of diet (Newport, 1981). Likewise, biotin supplementation at levels varying from 110 to 880 µg/kg of diet yielded no improvement in rate or efficiency of gain in pigs weaned at 21 to 28 days of age or in growing-finishing pigs (Peo et al., 1970; Hanke and Meade, 1971; Meade, 1971; Washam et al., 1975; Simmins and Brooks, 1980; Easter et al., 1983; Bryant et al., 1985b; Hamilton and Veum, 1986). Exceptions include one experiment that Adams et al. (1967) reported for growing pigs and one experiment that Peo et al. (1970) reported for pigs weaned at 28 days of age. Also, Partridge and McDonald (1990) observed feed efficiency responses to biotin when it was added to wheat–barley–soybean meal diets for growing pigs.

With sows, biotin supplementation has been reported to improve hoof hardness and compression, compressive strength, and the condition of skin and hair coat, as well as to reduce hoof cracks and footpad lesions (Grandhi and Strain, 1980; Webb et al., 1984; Bryant et al., 1985a,b; Simmins and Brooks, 1985; Misir and Blair, 1986). However, in studies by Hamilton and Veum (1984) and Tribble et al. (1984), no such improvements were recorded.

Lewis et al. (1991) reported that adding 0.33 mg/kg of biotin to a corn–soybean meal diet for sows during both gestation and lactation increased the number of pigs weaned but did not improve foot health. Watkins et al. (1991) also conducted a large-scale biotin efficacy trial for sows during gestation and lactation and reported that none of the criteria of reproductive performance, progeny development, or foot health responded to 0.44 mg of supplemental biotin/kg of diet. Other studies by investigators using a variety of grain sources have resulted in inconsistent results (Brooks et al., 1977; Penny et al., 1981; Easter et al., 1983; Simmins and Brooks, 1983; Hamilton and Veum, 1984; Tribble et al., 1984; Bryant et al., 1985c; Kornegay, 1986; Misir and Blair, 1984). A lack of consistency among experiments and a wide range of biotin supplementation levels (0.1 to 0.55 mg/kg of diet) make it difficult to establish a specific biotin requirement for sows.

Biotin deficiency signs include excessive hair loss, skin ulcerations and dermatitis, exudate around the eyes, inflammation of the mucous membranes of the mouth, transverse cracking of the hooves, and the cracking or bleeding of the footpads (Cunha et al., 1946, 1948; Lindley and Cunha, 1946; Lehrer et al., 1952). Biotin deficiency in pigs has been produced by feeding pigs synthetic diets containing sulfa drugs, which presumably reduce the synthesis of biotin in the intestinal tract (Lindley and Cunha, 1946; Cunha et al., 1948; Lehrer et al., 1952). Incorporation of large amounts of desiccated egg white in synthetic diets also has precipitated biotin deficiency in pigs (Cunha et al., 1946; Hamilton et al., 1983). Avidin, contained in raw egg white, forms a complex with biotin in the intestinal tract, rendering the vitamin unavailable to the pig.

Choline

Choline remains in the water-soluble vitamin category even though the quantity required far exceeds the "trace organic nutrient" definition of a vitamin. It is generally added to swine diets as choline chloride, which contains 74.6% choline activity (Emmert et al., 1996). Choline is required for (a) phospholipid (i.e., lecithin) synthesis, (b) acetyl choline formation, and (c) transmethylation of homocysteine to methionine, which occurs via betaine, the oxidation product of choline. When severe choline deficiency is encountered, phospholipid and acetyl choline synthesis take priority over the methylation functions of choline; however, grain–oilseed meal diets contain enough choline such that betaine or choline is equally efficacious on a molar basis in meeting the methylation function of choline (Lowry et al., 1987).

Pigs synthesize choline by methylating phosphatidyl ethanolamine in a three-step process involving methyl transfer from S-adenosylmethionine. Thus, excess dietary methionine can eliminate the dietary need for choline in pigs (Neumann et al., 1949; Nesheim and Johnson, 1950; Kroening and Pond, 1967).

Choline in soybean meal has been estimated to be 65 to 83% bioavailable relative to choline from choline chloride (Molitoris and Baker, 1976; Emmert and Baker, 1997). Analytical and bioavailability studies with chicks have indicated that dehulled soybean meal contains 2,218 mg of total choline/kg and 1,855 mg of bioavailable choline/kg; bioavailability of choline in peanut meal (71%) was slightly less than that in soybean meal (83%) and the choline in canola meal was only 24% bioavailable (Emmert and Baker, 1997). Because soy products are rich in bioavailable choline, starting, growing, and finishing pigs have not shown responses to supplemental choline when it was added to corn-soybean meal or corn–isolated soy protein diets (Russett et al., 1979a; North Central Region-42 Committee on Swine Nutrition, 1980). A portion of the choline present in feed ingredients and unprocessed fat sources exists as phospholipid-bound choline. This form of choline is thought to be utilized well (Emmert et al., 1996), but refined oils have been subjected to degumming, and this process removes virtually all of the phospholipid-bound choline (Anderson et al., 1979).

Feeding pregnant gilts and sows grain–soybean meal diets supplemented with 434 to 880 mg of choline/kg has generally increased the number of live pigs born and weaned (Kornegay and Meacham, 1973; Stockland and Blaylock, 1974; North Central Region-42 Committee on Swine Nutrition, 1976; Grandhi and Strain, 1980). In a long-term reproduction study, Stockland and Blaylock (1974) also reported that choline supplementation of corn–soybean meal diets improved conception rate. Gilts fed a choline-supplemented diet during gestation farrowed heavier pigs, but the incidence of spraddle-legged pigs was not reduced in four trials reported by Luce et al. (1985). During lactation, choline supplementation of diets containing 8 to 10% fat or oil did not improve lactation performance (Seerley et al., 1981; Boyd et al., 1982).

Choline-deficient pigs have reduced weight gain, rough hair coats, decreased red blood cell counts and hematocrit and hemoglobin concentrations, increased plasma alkaline phosphatase, and unbalanced and staggering gaits. Livers and kidneys exhibit fat infiltration. In a severe choline deficiency, kidney glomeruli can become occluded from massive fat infiltration (Wintrobe et al., 1942; Johnson and James, 1948; Neumann et al., 1949; Russett et al., 1979a).

The addition of 260 mg of choline/kg to a diet consisting of 30% vitamin-free casein, 37% glucose, 26.6% lard, and 2% sulfathaladine, which contained 0.8% methionine, prevented a choline deficiency in neonatal pigs (Johnson and James, 1948). A level of 1,000 mg of choline/kg of diet solids optimized weight gain and feed efficiency and prevented fat infiltration of the liver and kidneys in 2-day-old pigs (Neumann et al., 1949). Further addition of 0.8% DL-methionine to this diet did not improve the performance of pair-fed pigs supplemented with 1,000 mg of choline/kg of diet (Nesheim and Johnson, 1950). Kroening and Pond (1967) fed 5-kg pigs a low-protein (12%) diet supplemented with three levels of DL-methionine: 0, 0.11, or 0.22%. The addition of 1,646 mg of choline/kg of diet tended to improve the weight gains and feed conversion of pigs fed the two lower levels of methionine but not those of pigs fed the diet containing 0.22% supplemental methionine. Russett et al. (1979a,b) reported a minimum choline requirement of 330 mg/kg of diet for 6- to 14-kg pigs fed a semisynthetic diet containing 0.31% methionine and 0.33% cystine.

No signs of choline toxicity have been reported in swine (NRC, 1987), but daily gain reductions have been observed in pigs fed diets containing 2,000 mg of added choline/kg during the starting, growing, and finishing stages (Southern et al., 1986).

Folacin

Folacin includes a group of compounds with folic acid activity. Chemically, folacin consists of a pteridine ring, paraaminobenzoic acid (PABA), and glutamic acid. Animal cells cannot synthesize PABA, nor can they attach glutamic acid to pteroic acid. A deficiency of folacin causes a disturbance in the metabolism of single-carbon compounds, including the synthesis of methyl groups, serine, purines, and thymine. Folacin is involved in the conversion of serine to glycine and homocysteine to methionine.

The folacin present in feedstuffs exists primarily as a polyglutamate conjugate containing a γ-linked polypeptide chain of seven glutamic acid residues. A group of intestinal enzymes known as conjugases (folyl polyglutamate hydrolases) remove all but the last glutamate residue. Only the monoglutamyl form is thought to be absorbed into the intestinal enterocyte. Most of the folacin taken up by the intestinal brush border is reduced to tetrahydrofolic acid (FH_4) and then methylated to 5N-methyl FH_4. Like thiamin, folacin has a free amino group (on the pteridine ring), and this makes it heat-labile, particularly in diets containing reducing sugars such as dextrose or lactose.

Except for the studies by Matte et al. (1984a,b, 1992) and Lindemann and Kornegay (1989), results have indicated that the folacin contribution of ingredients commonly fed to swine when combined with bacterial synthesis within the intestinal tract adequately meets the requirement for all classes of swine.

Supplementation of a corn–soybean meal diet with 200 μg of folic acid/kg of diet during pregnancy did not increase the number of pigs born alive or weaned (Easter et al., 1983). Matte et al. (1984a) administered 15 mg of folic acid intramuscularly to sows 10 times, beginning at weaning and continuing until day 60 of pregnancy. They reported a significant increase in litter size farrowed. In a subsequent study, Matte et al. (1992) observed an increase in litter growth rate when the gestation diet was supplemented with 5 or 15 mg of folic acid/kg. Supplementation of the lactation diet, however, did not improve performance of the offspring. Lindemann and Kornegay (1989) also observed increased litter size at birth, but not at weaning, when the corn–soybean meal diet fed to sows was supplemented with 1 mg/kg of folacin. In a study by Tremblay et al. (1986), 4.3 mg of supplemental folic acid/kg of diet (diet containing 0.62 mg of folic acid/kg) maintained serum folate concentrations equivalent to those of pregnant sows injected with folic acid at various intervals from weaning to 56 days after mating (10 injections of 15 mg/sow). In a large multiparity study involving 393 sows, addition of 1, 2, or 4 mg of folic acid/kg to standard corn–soybean meal diets during premating, gestation, and lactation had no beneficial effects on reproductive performance (Harper et al., 1994). Based on these recent studies, the folacin requirement for gestating and lactating sows was increased to 1.3 mg/kg of diet.

Folacin deficiency in pigs leads to slow weight gain, fading hair color, macrocytic or normocytic anemia, leukopenia, thrombopenia, reduced hematocrit, and bone marrow hyperplasia. Synthetic diets, generally with the inclusion of 1 to 2% sulfa drugs or folic acid antagonists, have been fed to produce folacin deficiency in pigs (Cunha et al., 1948; Heinle et al., 1948; Cartwright et al., 1949, 1950; Johnson et al., 1950). Sulfa drugs presumably reduce bacterial synthesis of folacin in the intestinal tract. Folic acid supplementation did not affect the performance of 4-day-old pigs fed a synthetic diet that included 2% sulfathaladine (Johnson et al., 1948) or of 8-week-old pigs fed a synthetic diet (Cunha et al., 1947). Newcomb and Allee (1986) reported no beneficial effects from the addition of 1.1 mg of folic acid/kg to a corn–soybean meal–whey diet for pigs weaned at 17 to 27 days of age. However, Lindemann and Kornegay (1986) observed an improved daily weight gain in pigs of similar age fed a corn–soybean meal diet supplemented with 0.5 mg of folic acid/kg of diet. Pigs fed corn–soybean meal diets during the starting, growing, and finishing phases gained weight and used their feed as efficiently as those supplemented with 200 or 360 μg of folic acid/kg of diet (Easter et al., 1983; Gannon and Liebholz, 1989).

Niacin

Niacin or nicotinic acid is a component of the coenzymes nicotinamide-adenine dinucleotide (NAD) and nicotinamide-adenine dinucleotide phosphate (NADP). These coenzymes are essential for the metabolism of carbohydrates, proteins, and lipids.

Metabolic conversion of excess dietary tryptophan to niacin has complicated the determination of the niacin requirement (Luecke et al., 1948; Powick et al., 1948). Firth and Johnson (1956) estimated that each 50 mg of tryptophan in excess of the tryptophan requirement yields 1 mg of niacin. Niacin status is further complicated by its limited bioavailability in certain feed ingredients. The niacin in yellow corn, oats, wheat, and grain sorghum is in a bound form that is largely unavailable to young pigs (Kodicek et al., 1956; Luce et al., 1966, 1967; Harmon et al., 1969, 1970). The niacin in soybean meal, however, is highly available for the chick and is probably equally available for the pig (Yen et al., 1977).

Niacin activity is commercially available as either free nicotinic acid or free nicotinamide (niacinamide). Relative to nicotinic acid, nicotinamide is 124% bioavailable for chicks (Oduho and Baker, 1993) and 109% bioavailable for rats (Carter and Carpenter, 1982).

Firth and Johnson (1956) estimated the available niacin requirements for 1- to 8-kg pigs to be about 20 mg/kg for a diet with no excess tryptophan. Requirement estimates for growing pigs weighing 10 to 50 kg are 10 to 15 mg of available niacin/kg for diets containing tryptophan amounts near the requirement (Braude et al., 1946; Kodicek et al., 1959; Harmon et al., 1969). Growing-finishing diets are usually fortified with niacin, but studies with 45-kg pigs fed corn–soybean meal diets have indicated no performance improvements due to niacin supplementation (Yen et al., 1978; Copelin et al., 1980); the diets used in these experiments, however, contained calculated tryptophan amounts that were in excess of the requirement. However, in a study in a commercial facility in which levels of 0, 13, 28, 55, 110, and 550 mg/kg of diet were evaluated (Real et al., 2002), increasing added niacin improved gain:feed (quadratic, $P < 0.01$) and subjective color score and ultimate pH (linear, $P < 0.01$). Added niacin also decreased (linear, $P < 0.04$) carcass shrink and drip loss percentage. Results showed that 13 mg added dietary niacin/kg was the amount needed to improve gain:feed and that higher levels of supplementation are needed to fully realize attainable benefits in carcass and pork quality.

There is little information on the niacin requirement of pregnant and lactating sows. Ivers et al. (1993) concluded, after following 67 sows over 5 parities for a total of 240 litters, that a 12.80% CP corn–soybean meal–oats diet without supplementation provided adequate niacin during gestation and lactation. More recently, Mosnier et al. (2009) reported that niacin and vitamin B_6 could be transiently suboptimal in early lactation. Plasma concentrations of tryptophan and niacin decreased during the week after parturition while plasma kynurenine (an intermediate in the conversion of tryptophan to niacin) increased. During the second and third weeks of lactation, plasma tryptophan and kynurenine returned to prefarrowing concentrations, while niacin increased throughout lactation. Vitamin B_6 (a vitamin involved in this conversion and utilization of niacin) also increased progressively during the week after farrowing and remained constant at a high concentration thereafter. Further research is needed to establish if niacin is needed during the first week and whether that niacin level could be impacting protein utilization in situations of marginal tryptophan supply.

Research with chicks has demonstrated that iron deficiency impairs the efficacy of tryptophan as a niacin precursor (Oduho et al., 1994). Whether this relationship occurs in pigs is unknown. Iron is required as a cofactor for two enzymes in the pathway leading to nicotinic acid mononucleotide synthesis from tryptophan.

Niacin deficiency signs include reduced weight gain, inappetence, vomiting, dry skin, dermatitis, rough hair coat, hair loss, diarrhea, mucosal ulcerations, ulcerative gastritis, inflammation and necrosis of the cecum and colon, and normocytic anemia (Hughes, 1943; Braude et al., 1946; Wintrobe et al., 1946; Luecke et al., 1947; Powick et al., 1947a,b; Cartwright et al., 1948; Burroughs et al., 1950; Kodicek et al., 1956). Blood erythrocyte NAD activity and urinary excretions of N-methyl-nicotinamide and N′-methyl-2-pyridone-5-carboxamide are reduced in niacin deficiency (Luce et al., 1966, 1967).

Pantothenic Acid

This B-vitamin consists of pantoic acid joined to β-alanine by an amide bond. As a component of coenzyme A, pantothenic acid is important in the catabolism and synthesis of two-carbon units evolved during carbohydrate and fat metabolism. Biological availability of pantothenic acid is low in barley, wheat, and sorghum but is high in corn and soybean meal (Southern and Baker, 1981). In feedstuffs, most of the pantothenic acid exists as coenzyme A, acyl CoA synthetase, and acyl carrier protein. Only the D-isomer of pantothenic acid is biologically active. Synthetic pantothenic acid is generally added to all swine diets as calcium pantothenate, a salt that is more stable than pantothenic acid. The D-form of calcium pantothenate has 92% activity; the racemic mixture of the calcium salt contains only 46% active pantothenic acid. A DL-calcium pantothenate–calcium chloride complex is also available, and it contains 32% activity.

The pantothenic acid requirement of 2- to 10-kg pigs fed synthetic diets was 15.0 mg/kg (Stothers et al., 1955); and for 5- to 50-kg pigs, estimates range from about 4.0 to 9.0 mg/kg of diet (Luecke et al., 1953; Barnhart et al., 1957; Sewell et al., 1962; Palm et al., 1968). Requirement estimates for pigs weighing between 20 and 90 kg have varied from 6.0 to 10.5 mg of pantothenic acid/kg of diet (Catron et al., 1952; Pond et al., 1960; Davey and Stevenson, 1963; Palm et al., 1968; Roth-Maier and Kirchgessner, 1977). In a more recent examination (Groesbeck et al., 2007), it seemed that the pantothenic acid in corn and soybean meal may be sufficient to meet the requirements of 25- to 120-kg pigs.

Ullrey et al. (1955), Davey and Stevenson (1963), and Teague et al. (1970) reported poor reproductive performance in three experiments when the pantothenic acid level was below 5.9 mg/kg of diet; Bowland and Owen (1952), however, reported normal reproductive performance at this level. Ullrey et al. (1955) and Davey and Stevenson (1963) estimated the pantothenic acid requirement for optimal reproduction at 12.0 to 12.5 mg/kg of diet.

Pantothenic acid deficiency signs include slow growth, inappetence, diarrhea, dry skin, rough hair coat, alopecia, reduced immune response, and an abnormal movement of the hind legs called goose stepping (Hughes and Ittner, 1942; Wintrobe et al., 1943b; Luecke et al., 1948, 1950, 1952; Wiese et al., 1951; Stothers et al., 1955; Harmon et al., 1963). Postmortem findings in pigs with pantothenic acid deficiency include edema and necrosis of the intestinal mucosa, increased connective tissue invasion of the submucosa, loss of nerve myelin, and degeneration of dorsal root ganglion cells (Wintrobe et al., 1943b; Follis and Wintrobe, 1945).

Riboflavin

A component of two coenzymes, flavin mononucleotide (FMN) and flavin adenine dinucleotide (FAD), riboflavin is important in the metabolism of proteins, fats, and carbohydrates. In feedstuffs, most of the riboflavin activity exists as FAD.

Estimates of the riboflavin requirement for pigs weighing 2 to 20 kg range from 2.0 to 3.0 mg/kg of synthetic diet (Forbes and Haines, 1952; Miller et al., 1954). Riboflavin requirement estimates range from 1.1 to 2.9 mg/kg for growing pigs fed synthetic diets (Hughes, 1940a; Krider et al., 1949; Mitchell et al., 1950; Terrill et al., 1955), whereas the estimates vary from 1.8 to 3.1 mg/kg of diet when practical diets are fed (Krider et al., 1949; Miller and Ellis, 1951). Seymour et al. (1968) reported no consistent interactions between riboflavin level and environmental temperature for 5- to 17-kg pigs, a finding that contradicted an earlier report by Mitchell et al. (1950). Corn–soybean meal diets are deficient in bioavailable riboflavin. In a study with chicks, Chung and Baker (1990) estimated that the riboflavin in corn–soybean meal diets is 59% bioavailable relative to crystalline riboflavin.

Riboflavin deficiency has led to anestrus (Esch et al., 1981) and reproductive failure in gilts (Miller et al., 1953; Frank et al., 1984). On the basis of farrowing performance and erythrocyte glutathione reductase activity (FAD-dependent enzyme), Frank et al. (1984) estimated the available riboflavin requirement for pregnancy to be about 6.5 mg daily. Pettigrew et al. (1996), however, observed that 60 mg of riboflavin/day produced a higher farrowing rate than 10 mg/day when these levels were fed from breeding to day 21 of gestation. Erythrocyte glutathione reductase activity and farrowing performance suggest a lactation requirement of about 16 mg of riboflavin daily (Frank et al., 1988).

Signs of riboflavin deficiency in young growing pigs include slow growth, cataracts, stiffness of gait, seborrhea, vomiting, and alopecia (Wintrobe et al., 1944; Miller and Ellis, 1951; Lehrer and Wiese, 1952; Miller et al., 1954). In severe riboflavin deficiency, researchers have observed increased blood neutrophil granulocytes, decreased immune response, discolored liver and kidney tissue, fatty liver, collapsed follicles, degenerating ova, and degenerating myelin of the sciatic and brachial nerves (Wintrobe et al., 1944; Krider et al., 1949; Mitchell et al., 1950; Forbes and Haines, 1952; Lehrer and Wiese, 1952; Miller et al., 1954; Terrill et al., 1955; Harmon et al., 1963).

Thiamin

Thiamin is essential for carbohydrate and protein metabolism. The coenzyme, thiamin pyrophosphate, is essential for the oxidative decarboxylation of α-keto acids. Thiamin is very heat-labile. Therefore, excess heat or autoclaving can reduce the thiamin content of dietary components, particularly when reducing sugars are present.

Miller et al. (1955) estimated a thiamin requirement of 1.5 mg/kg for pigs weighing about 2 kg initially and fed to approximately 10 kg of body weight. Pigs weaned at 3 weeks and fed to about 40 kg of body weight required about 1.0 mg of thiamin/kg of diet (Van Etten et al., 1940; Ellis and Madsen, 1944). The survival time of thiamin-deficient pigs was increased by increasing fat levels to 28% of the diet (Ellis and Madsen, 1944). This finding indicated that the requirement for thiamin was decreased as the dietary energy from carbohydrate was replaced with higher amounts of fat. Weight gain was improved by increasing thiamin levels to 1.1 mg/kg of diet, whereas feed intake was maximized at 0.85 mg/kg of diet for pigs weighing about 30 kg and fed to 90 kg of body weight (Peng and Heitman, 1974). Peng and Heitman (1973) evaluated the thiamin status of growing-finishing pigs by measuring the increase in erythrocyte transketolase activity resulting from thiamin pyrophosphate addition to in vitro preparations. This criterion yielded thiamin requirement estimates up to four times the amount required for maximum weight gain. Furthermore, the requirement measured by this criterion increased as environmental temperature increased from 20 to 35°C (Peng and Heitman, 1974). This change was probably related to a reduction in feed intake. There is a lack of information on the thiamin requirement for pregnancy and lactation.

Treatment of feed ingredients with sulfur dioxide inactivates thiamin. This process was used in early studies to produce deficient diets for purposes of determining a pig's thiamin requirement (Van Etten et al., 1940; Ellis and Madsen, 1944). A number of freshwater fish species contain an antithiamin factor known as thiaminase I (Tanphaichitr and Wood, 1984). Feeding moderate amounts of unprocessed freshwater fish preparations to other animals can cause a thiamin deficiency (Green et al., 1941; Krampitz and Woolley, 1944).

Thiamin-deficient pigs exhibit loss of appetite; a reduction in weight gain, body temperature, and heart rate; and, occasionally, vomiting. Other effects observed in thiamin deficiency are heart hypertrophy, flabby heart, myocardial degeneration, and sudden death because of heart failure.

Animals deficient in thiamin also have elevated plasma pyruvate concentrations (Hughes, 1940b; Van Etten et al., 1940; Follis et al., 1943; Wintrobe et al., 1943a; Ellis and Madsen, 1944; Heinemann et al., 1946; Miller et al., 1955). Most of the cereal grains used in swine diets are rich in thiamin. Hence, grain–oilseed meal diets fed to all classes of swine are considered adequate in this B-vitamin, and it is not generally included as a supplement for swine diets.

Vitamin B_6 (The Pyridoxines)

Vitamin B_6 occurs in feedstuffs as pyridoxine, pyridoxal, pyridoxamine, and pyridoxal phosphate. Pyridoxal phosphate is an important cofactor for many amino acid enzyme systems, including transminases, decarboxylases, dehydratases, synthetases, and racemases. Vitamin B_6 plays a crucial role in central nervous system function. It is involved in the decarboxylation of amino acid derivatives for the synthesis of neurotransmitters and neuroinhibitors.

Vitamin B_6 in corn and soybean meal is about 40 and 60% bioavailable for the chick, respectively (Yen et al., 1976). Presumably, it is the same in pigs, although data are not available. Miller et al. (1957) and Kösters and Kirchgessner (1976a,b) suggested a dietary requirement of 1.0 to 2.0 mg/kg of diet for the pig weighing initially about 2 kg and fed to 10 kg of body weight. Historical requirement estimates for the 10- to 20-kg pig range have been from 1.2 to 1.8 mg of vitamin B_6/kg of diet (Sewell et al., 1964; Kösters and Kirchgessner, 1976a,b). However, more recent research has demonstrated with semipurified diets (Zhang et al., 2009) as well as with conventional diets (Woodworth et al., 2000) that the requirement for the young pig is higher than former estimates and approaches 7 mg/kg of diet in the immediate postweaning period.

Ritchie et al. (1960) reported no treatment differences in reproductive or lactation performance in gilts and sows fed diets containing total pyroxidine levels of either 1.0 or 10.0 mg/kg from the second month of pregnancy through day 35 of lactation. Easter et al. (1983) reported an increase in litter size at birth and at weaning when 1.0 ppm of pyridoxine was added to a corn–soybean meal diet fed to gilts during pregnancy. In another study, the coefficients of glutamic-oxaloacetic transaminase activity in red blood cells of sexually mature gilts fed 0.45 and 2.1 mg of vitamin B_6/day were elevated compared with those of gilts fed an excess amount of 83 mg of vitamin B_6/day. Whole-muscle glutamic-oxaloacetic transaminase activity was reduced in deficient gilts; this reduction suggests that the daily requirement for vitamin B_6 may be greater than 2.1 mg (Russell et al., 1985a,b). More recently, Knights et al. (1998) evaluated two dietary supplemental pyridoxine levels (1.0 vs. 15.0 ppm) and the overall results indicated that increased dietary pyridoxine tended to have a positive influence on sow weaning to estrus interval and nitrogen metabolism. The wide range of treatments examined makes the establishment of a requirement level difficult.

A deficiency of vitamin B_6 will reduce appetite and growth rate. Advanced deficiency will result in an exudate development around the eyes, convulsions, ataxia, coma, and death. Blood samples from deficient pigs show a reduction in hemoglobin, red blood cells, and lymphocyte counts. Serum iron and gamma globulin are increased. Peripheral myelin and axis cylinder degeneration of the sensory neurons, microcytic hypochromic anemia, and fat infiltration of the liver are characteristic of vitamin B_6 deficiency (Hughes and Squibb, 1942; Wintrobe et al., 1942, 1943c; Follis and Wintrobe, 1945; Lehrer et al., 1951; Miller et al., 1957; Harmon et al., 1963). A tryptophan-loading test, in which the conversion of tryptophan to niacin is impaired, can determine vitamin B_6 status. This impairment results in elevated xanthurenic acid and kynurenic acid concentrations in the urine (Cartwright et al., 1944). Supplementation of grain–soybean meal diets with vitamin B_6 is generally unnecessary, because the amount of bioavailable vitamin B_6 in feed ingredients will meet the pig's requirement.

Vitamin B_{12}

Vitamin B_{12}, or cyanocobalamin, contains the trace element cobalt in its molecule, which is a unique feature among vitamins. Vitamin B_{12} as a coenzyme is involved in the de novo synthesis of labile methyl groups derived from formate, glycine, or serine, and their transfer to homocysteine to form methionine. It is also important in the methylation of uracil to form thymine, which is converted to thymidine and used for the synthesis of DNA. Pigs require vitamin B_{12}, but responses to dietary supplementation have been variable. Synthesis of vitamin B_{12} by microorganisms in the environment and within the intestinal tract as well as the pig's inclination toward coprophagy may supply sufficient vitamin B_{12} to satisfy the pig's requirement (Bauriedel et al., 1954; Hendricks et al., 1964). Ingredients of plant origin are devoid of vitamin B_{12}, but animal and fermentation byproducts contain the vitamin. In these ingredients, vitamin B_{12} exists in a methylated form (methylcobalamin) or a 5′-deoxyadenosyl form (adenosyl cobalamin), and both of these compounds are generally bound to protein. Vitamin B_{12} supplements are produced commercially by microbial fermentation and are usually added to grain–soybean meal diets.

Receptor sites for vitamin B_{12} binding are located in the ileum. Prior to absorption, cobalamin is bound to a glycoprotein, commonly referred to as "intrinsic factor." Intrinsic factor is derived from the parietal cells of gastric mucosa. Vitamin B_{12} is stored effectively in the body. Thus tissue storage, primarily in the liver, resulting from excess vitamin B_{12} ingestion can delay for many months the onset of vitamin B_{12} deficiency symptoms after a vitamin B_{12}-deficient diet is fed (Combs, 1999).

Estimated vitamin B_{12} requirements for 1.5- to 20-kg pigs fed synthetic milk diets and housed in wire-floored cages range from 15 to 20 μg/kg of dietary dry matter (Anderson and Hogan, 1950b; Nesheim et al., 1950; Frederick and Brisson, 1961), but as high as 50 µg/kg of diet dry matter in one study (Neumann et al., 1950). Pigs weighing about 10 to 45 kg required 8.8 to 11.0 µg of vitamin B_{12}/kg of diet (Richardson et al., 1951; Catron et al., 1952). The pigs in these experiments also were housed in wire-floored cages. If achieving a minimization of plasma homocysteine concentration is used as a response measure for nutritional need, then 30-35 µg/kg of diet may be an appropriate value (House and Fletcher, 2003).

Anderson and Hogan (1950a), Frederick and Brisson (1961), and Teague and Grifo (1966) reported improved the reproductive performance of sows by adding 11 to 1,100 µg of vitamin B_{12}/kg of diet. Teague and Grifo (1966) compared the reproductive performance of sows fed an unsupplemented all-plant diet with that of a diet supplemented with 110 to 1,100 µg of vitamin B_{12}/kg. Until the sows' third and fourth parities, there was no reduction in the number of pigs farrowed or weaned, or in their weights at birth or weaning. Simard et al. (2007) examined the effects of five concentrations of cyanocobalamin (0, 20, 100, 200, or 400 µg/kg) administered throughout gestation on sow plasma B_{12} and homocysteine (a detrimental intermediate metabolite of the vitamin B_{12}-dependent remethylation pathway). Based on a broken-line regression model, the concentrations of dietary cyanocobalamin that maximized plasma vitamin B_{12} and minimized plasma homocysteine of sows during gestation were estimated to be 164 and 93 µg/kg, respectively. While there appeared to be some benefits also in litter size, the authors concluded that the biological significance of such concentrations of cyanocobalamin need to be validated with performance criteria by using greater numbers of animals during several parities. Because of the wide range of levels supplemented and the few experiments, it is difficult to determine the vitamin B_{12} requirement for reproduction and lactation, but it is estimated at 15 µg/kg of diet.

Pigs that are deficient in vitamin B_{12} have reduced weight gain, loss of appetite, rough skin and hair coat, irritability, hypersensitivity, and hind leg incoordination. Blood samples from deficient pigs indicate normocytic anemia and high neutrophil and low lymphocyte counts (Anderson and Hogan, 1950b; Neumann and Johnson, 1950; Neumann et al., 1950; Cartwright et al., 1951; Richardson et al., 1951; Catron et al., 1952). A deficiency of folic acid and vitamin B_{12} has led to macrocytic anemia and bone marrow hyperplasia, both of which have several similar characteristics to pernicious anemia in human beings (Johnson et al., 1950; Cartwright et al., 1952). Signs of folacin deficiency generally accompany vitamin B_{12} deficiency, because vitamin B_{12} is required for folate metabolism. Lack of either folacin or vitamin B_{12} prevents the proper transfer of methyl groups in the synthesis of thymidine.

Vitamin C (Ascorbic Acid)

Vitamin C (ascorbic acid) is a water-soluble antioxidant that is involved in the oxidation of aromatic amino acids, synthesis of norepinephrine and carnitine, and in the reduction of cellular ferritin iron for transport to the body fluids. Ascorbic acid is also essential for hydroxylation of proline and lysine, which are integral constituents of collagen. Collagen is essential for growth of cartilage and bone. Vitamin C enhances the formation of both bone matrix and tooth dentin. In vitamin C deficiency, petechial hemorrhages occur throughout the body. A dietary source of vitamin C is essential for primates and guinea pigs, but farm animals, including pigs, can synthesize this vitamin from D-glucose and several other related compounds (Braude et al., 1950; Dvorak, 1974; Brown and King, 1977). Strittmatter et al. (1978), Cleveland et al. (1983), and Nakano et al. (1983) have investigated the role of vitamin C in the prevention or alleviation of osteochondrosis in swine. These authors postulated that osteochondrosis might be related to insufficient collagen cross-linking because of reduced hydroxylation of lysine. Dietary supplementation with vitamin C, however, was ineffective in preventing this malady.

Under some conditions, pigs may not be able to synthesize vitamin C rapidly enough to meet their requirements. Riker et al. (1967) reported that plasma ascorbic acid concentrations were lower for pigs at an environmental temperature of 29°C than for pigs at 18°C. However, vitamin C supplementation of pigs housed at temperatures of either 19 or 27°C did not improve rate or efficiency of weight gain (Kornegay et al., 1986). Brown et al. (1970) found a significant correlation between energy intake and serum ascorbic acid levels, and later reported that vitamin C supplementation significantly improved the rate of weight gain of 3-week-old pigs (Brown et al., 1975). There was a greater response to vitamin C at a low energy intake than at an intermediate or a high energy intake. The concentration and total amount of ascorbic acid in the liver of 1- or 40-day-old pigs were reduced in fasted pigs compared with that in suckling pigs (Dvorak, 1974). There also are reports of improved weight gains in response to supplemental vitamin C in the diet when no deliberate stress had been imposed on pigs. Jewell et al. (1981) reported improved weight gain from vitamin C supplementation in 1-day-old weaned pigs in one trial, but no response to the supplement in a second trial. Using pigs weaned at 3 to 4 weeks of age, Brown et al. (1975), Yen and Pond (1981), and Mahan et al. (1994) reported that weight gains were improved by supplementing the diet with vitamin C. In pigs weighing 24 kg initially, Mahan et al. (1966) observed an improvement in weight gain from parenteral dosing and feed supplementation with vitamin C. In two of three trials, growing pigs (15 to 27 kg) fed to about 90 kg of body weight responded to vitamin C supplementation (Cromwell et al., 1970). Others have noted no improvement in performance from vitamin C supplementation in suckling pigs,

pigs weaned at 3 to 4 weeks of age, or growing-finishing pigs (Hutagalung et al., 1969; Leibbrandt, 1977; Strittmatter et al., 1978; Mahan and Saif, 1983; Nakano et al., 1983; Yen and Pond, 1984; Yen et al., 1985; Kornegay et al., 1986). Mahan et al. (1994) observed no beneficial effects from adding vitamin C to corn–soybean meal diets fed to growing-finishing pigs. Chiang et al. (1985) has reviewed the effects of supplemental vitamin C for weanling and growing-finishing pigs. Bhar et al. (2003) reported benefit of supplementing vitamin C (50 mg/animal per day) wherein supplementation had a positive effect on wound healing, antibody response, and growth performance of pigs after injury.

Sandholm et al. (1979) reported a rapid cessation of navel bleeding in newborn pigs when 1.0 g of vitamin C/day was fed to pregnant sows beginning 5 days before expected farrowing. Pigs from sows given supplemental vitamin C were significantly heavier at 3 weeks of age than those from control sows. A water-soluble vitamin K administered in the drinking water to several sows in this herd failed to prevent the navel bleeding problem in newborn pigs. In subsequent studies, there was no improvement in pig survival or growth rate when sows were supplemented with 1.0 to 10.0 g of vitamin C/day beginning in late pregnancy (Lynch and O'Grady, 1981; Chavez, 1983; Yen and Pond, 1983). Navel bleeding was not considered to be a problem in these latter experiments.

If a supplemental vitamin C need exists, it would seem to be a transient need during times of stress when feed intake may be limited. However, because the conditions in which supplemental vitamin C may be beneficial are not well defined, and because of the apparent transient nature of the need, no vitamin C requirement estimate is given for pigs.

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8

Models for Estimating Nutrient Requirements of Swine

INTRODUCTION

It has been well established that dietary nutrient requirements differ among groups of swine and are influenced by the animal's physiological state, performance potential, and environmental conditions (NRC, 1998). The three mathematical models that were presented in NRC (1998) have been updated and adjusted to estimate requirements for standardized ileal digestible (SID) amino acids, and nitrogen (N), standardized total tract digestible (STTD) phosphorus (P), and total calcium (Ca) of (1) growing-finishing pigs between 20 and 140 kg live body weight (BW), (2) gestating sows and (3) lactating sows. During model development, ease of use, transparency, and simplicity have been balanced with predictive accuracy and practical relevance. Estimates of apparent ileal digestible (AID) amino acid and apparent total tract digestible (ATTD) P requirements are derived from SID amino acid and STTD P requirements, respectively. For corn and soybean meal–based diets, estimates of total dietary amino acid and P requirements are generated as well. Nutrient requirements of pigs below 20 kg BW and requirements for vitamins and minerals other than P and Ca have been estimated empirically and integrated in the models for completeness. The models are complemented with a simple feed formulation routine that allows for a direct comparison of calculated diet nutrient contents with model-generated estimates of nutrient requirements.

The three models are mechanistic, dynamic, and deterministic in representing the biology of nutrient and energy utilization at the whole-animal level. The models can be considered mechanistic in that they mathematically represent the biological principles that are known to influence nutrient requirements. These biological principles have been outlined in Chapters 1 (Energy), 2 (Proteins and Amino Acids), and 6 (Minerals). However, and by necessity, the models contain empirical elements to make model-generated estimates of nutrient requirements consistent with empirical observations. Cumulative animal performance (growth, gestation, and lactation) is represented dynamically over a user-defined period of time based on iterative calculations with a 1-day iteration interval. Once dynamic simulations are executed, users can explore nutrient requirements on individual days or across days. Nutrient requirements across days are calculated simply as the average of requirements on individual days. The models are deterministic in that nutrient requirements are estimated for groups of animals without explicitly representing between-animal variability. However, between-animal variability is considered implicitly in the models by adjusting estimates of post-absorptive efficiencies of nutrient utilization from values that have been established in individual animals (e.g., Pomar et al., 2003), as outlined in Chapter 2 (Proteins and Amino Acids).

For estimating nutrient requirements of the various categories of swine, the model user has to specify levels of energy intake and animal performance. For growing-finishing pigs and lactating sows, routines have been added to generate rather simplified predictions of energy intake levels. Based on these inputs the models generate estimates of daily whole-body protein deposition (Pd), whole-body lipid deposition (Ld), and BW changes. For gestating sows, protein, lipid, and total weight gains of conceptus and reproductive tissues are also considered, while for nursing sows, litter size and mean daily piglet growth rates are used as measures of milk nutrient and milk energy output. Nutrient requirements to support observed animal performance are then generated. Because the animal's response to energy intake is estimated, the models cannot be used directly to generate estimates of energy requirements. The animal's response, either absolute or marginal, to suboptimal levels of nutrient intake is not represented in the models. As a consequence, the animal's nutrient requirements following a period of nutrient intake restriction, which may be influenced by potential compensatory growth, are not estimated.

Generated nutrient requirements relate to the animal's observed biological performance in a relatively disease and stress-free environment and do not reflect cost-benefit analyses. The potential impact of disease challenges or environmental conditions on nutrient requirements are not considered, except for effects of thermal environment on predicted energy intake and estimated maintenance energy requirements. Dietary nutrient intakes to yield maximum financial performance or maximum nutrient utilization efficiency may be different from the generated estimates of nutrient requirements.

In the models, the calculation unit for energy is "effective" metabolizable energy (ME). "Effective" ME, represented as ME throughout this text and in all equations, and "effective" digestible energy (DE) can be calculated from net energy (NE) based on fixed conversion factors that apply to typical corn and soybean meal–based diets; these typical diets represent those that have been used to generate estimates of partial energetic efficiencies. This concept has been described in detail in Chapter 1 (Energy).

In the three models, there is an option to enter observed changes in body composition (e.g., backfat thickness) and BW (e.g., growth performance of growing-finishing pigs, total BW changes during gestation, or sow BW changes during lactation), for comparing or matching model-predicted with observed values. When observed values are similar to model-predicted values, the user can have increased confidence in the model-generated estimates of nutrient requirements. Further detail is provided in the User Guide (distributed with the model) on how observed changes in body composition and BW can be matched to model-predicted values.

In this chapter, the mathematical approach to generating nutrient requirements is presented. Some of the equations are also presented in Chapters 1, 2, and 6, but are included here for completeness. More detailed descriptions of all model inputs and outputs, printouts of the main screens, and simple tutorials are presented in the User Guide (Appendix A).

GROWING-FINISHING PIG MODEL

Main Concepts

Growth is represented based on daily rates of Pd and Ld, which contribute to changes in whole-body protein mass (BP) and whole-body lipid mass (BL). In the model, Pd is used to characterize pig types (genotypes and gender) and levels of growth performance; Pd is considered a more objective and universal measure than lean tissue growth. Empty body weight (EBW) and BW are predicted from BP and BL. Energy intake is partitioned between energy requirements for body maintenance functions, Pd, and Ld. Since maintenance energy requirements are established in animals fed protein-containing diets and protein energy is thus considered part of energy intake, protein use for protein maintenance is not deducted from maintenance energy requirements. Maintenance energy requirements are predicted from BW and environmental temperature and may be adjusted by the model user to account for condition-specific requirements. Pig performance or potentials are characterized based on Pd curves, which can be defined either by the model user, related to energy intake, or estimated from observed growth performance. Energy intake that is not used for body maintenance functions and Pd is used for Ld. The SID amino acid and N requirements are estimated from Pd, BW, and feed intake. The STTD P requirements are derived from feed intake, Pd, and BW, while total Ca requirements are estimated from STTD P requirements. The AID and total amino acid requirements, as well as ATTD and total P requirements, are calculated from SID and STTD values based on nutrient profiles in corn and soybean meal–based diets that contain 3% premix and 0.1% lysine·HCl, and that are formulated to meet the SID amino acid and STTD P requirements.

The impacts of feeding ractopamine (RAC) and immunization of entire males against gonadotropin-releasing hormone (GnRH) on nutrient requirements are estimated by representing their impacts on ME intake, maintenance ME requirements, Pd, and, as a consequence, Ld. The RAC-induced Pd is tracked separately to represent its impact on the amino acid composition of Pd and body composition.

The dynamic model includes mathematical equations to represent changes in energy intake, Pd, and BW gain with increasing BW. Two alternative equations are available to represent each of these relationships. The polynomial equations are easy to use and can be parameterized relatively easily using spreadsheets such as Microsoft® Excel. The alternative equations are asymptotic or sigmoidal functions and are more representative of biological relationships, but will require more advanced statistical packages for parameterization. Typical energy intake and Pd curves are included for gilts, barrows, and entire males as defaults.

Body Composition

Chemical and physical body compositions are represented mathematically as outlined in a recent review (de Lange et al., 2003). The sum of the four chemical body constituents—BL, BP, whole-body water mass (Wat), and whole-body ash mass (Ash)—represents EBW (Eq. 8-1). Both Wat and Ash are related directly to BP and are all expressed in kilograms (Eqs. 8-2 and 8-3). In the relationship between Wat and BP, the pig's operational upper limit to Pd (Pd_{Max}; highest value in the Pd curve; g/day) is considered as well. Gut fill is predicted from BW (at the initial BW, kg; Eq. 8-4) or EBW (at subsequent BW, kg; Eq. 8-5). Gut fill and EBW make up BW. Largely because of the allometric relationship between Wat and BP, the chemical compositions of both BW gain, as well as lean tissue gain, vary with stage of growth and pig type (Emmans and Kyriazakis, 1995).

$$\text{EBW (kg)} = \text{BP} + \text{BL} + \text{Wat} + \text{Ash} \quad \text{(Eq. 8-1)}$$

$$\text{Wat (kg)} = (4.322 + 0.0044 \times Pd_{Max}) \times P^{0.855} \quad \text{(Eq. 8-2)}$$

$$\text{Ash (kg)} = 0.189 \times BP \quad \text{(Eq. 8-3)}$$

$$\text{Gut fill (kg)} = 0.277 \times BW^{0.612} \quad \text{(Eq. 8-4)}$$

$$\text{Gut fill (kg)} = 0.3043 \times EBW^{0.5977} \quad \text{(Eq. 8-5)}$$

An iterative procedure (the Newton-Raphson method; Arfken, 1985) is used to estimate chemical body composition from BW at the initial BW and based on an estimated BL to BP ratio (BL/BP) (Eq. 8-6).

$$\text{BL/BP at initial BW} = (0.305 - 0.000875 \times Pd_{Max}) \times BW^{0.45} \quad \text{(Eq. 8-6)}$$

For the estimation of carcass lean content, a standard measure of backfat thickness is used. Probe backfat thickness is monitored routinely in many regions of the world and increasingly in North America (Fortin et al., 2004; Schinckel et al., 2010b). It is typically measured with an optical probe between the third- and fourth-last rib and 7 cm from the midline on the hot carcass. The relationship between chemical body composition and probe backfat thickness (Eq. 8-7) was based on additional analyses of a large data set (Wagner et al., 1999; Schinckel et al., 2001, 2010b), and was tested on data from Quiniou (1995; original analyses conducted by P. Morel, Massey University, New Zealand). Given the potential errors in measuring backfat thickness and its impact on the prediction of carcass lean content, this parameter has to be interpreted with caution (Johnson et al., 2004; Schinckel et al., 2006). The relationship between probe backfat thickness and carcass lean content varies with the definition and method for estimation of carcass lean content and can be influenced by pig genotype and gender. The default equation in the model (Eq. 8-8) provides a reasonable prediction of carcass fat-free lean tissue content according to the National Pork Producers Council (NPPC; National Pork Board, 2000), but may be adjusted to specific conditions. Based on this equation, carcass fat-free lean gain may be predicted as Pd × 2.55 (NRC, 1998). However, this relationship is only valid over a wide BW range (e.g., 25-125 kg BW) and will provide an underestimate of fat-free lean tissue gain in pigs with high Pd_{Max}. Model users may adjust parameters in Eq. 8-8 and the ratio between fat-free lean gain and Pd to local conditions.

$$\text{Probe backfat thickness (mm)} = -5 + 12.3 \times BL / BP + 0.13 \times BP \quad \text{(Eq. 8-7)}$$

$$\text{NPPC carcass fat-free lean content (\%)} = 62.073 + 0.0308 \times \text{Carcass weight} - 1.0101 \times \text{Probe backfat thickness} + 0.00774 \times (\text{Probe backfat thickness})^2 \quad \text{(Eq. 8-8)}$$

Energy and Feed Intake

The growing-finishing pig model includes three options to generate estimates of ME intake at the various BW. Firstly, a simple prediction of ME intake can be generated as a function of BW (kg), considering: (1) gender, (2) physical feed intake capacity, (3) environmental temperature (optional), and (4) pig density (optional). Secondly, an ME intake curve can be generated from observed feed intake over a defined BW range, which is then used in combination with the reference ME intake curve. Thirdly, parameters in two types of equations can be entered by the model user to relate ME intake to BW.

Metabolizable energy intake is related to feed intake based on a user-defined diet ME content. An estimate of feed wastage, defined by the model user as feed intake over feed intake plus feed wastage, is required to relate predicted feed intake to predicted feed usage, or to relate observed feed usage to feed and ME intake. Typically, feed wastage represents 5% of feed that is delivered to the feeder, but it can vary between 3% and more than 10%. Adjusting the value entered for feed wastage illustrates the effects on nutrient requirements and the importance of reducing feed wastage.

The reference ME intake curve (Eq. 8-9) serves as a benchmark and may be used to extrapolate observed ME intake at a defined BW to ME intakes at other BW. The reference ME intake curve is equivalent to 83.6% of NRC (1987; also used in NRC, 1998). The reference ME intake curve is based on the Bridges function (Schinckel et al., 2009b), is equivalent to the average intake of gilts (Eq. 8-10) and barrows (Eq. 8-11), and has been adjusted to represent typical feed intake levels of pigs under practical conditions. It is important to emphasize that this reference intake curve does not include feed wastage. Energy intake of entire males is assumed to be 3% lower than that of gilts (Eq. 8-12).

$$\text{Reference ME intake (kcal/day)} = 10{,}563 \times \{1 - \exp[-\exp(-4.04) \times BW]\} \quad \text{(Eq. 8-9)}$$

For the three genders, separate default ME intake curves are used (Figure 8-1):

$$\text{Default ME intake, gilts (kcal/day)} = 10{,}967 \times \{1 - \exp[-\exp(-3.803) \times BW^{0.9072}]\} \quad \text{(Eq. 8-10)}$$

$$\text{Default ME intake, barrows (kcal/day)} = 10{,}447 \times \{1 - \exp[-\exp(-4.283) \times BW^{1.0843}]\} \quad \text{(Eq. 8-11)}$$

$$\text{Default ME intake, entire males (kcal/day)} = 10{,}638 \times \{1 - \exp[-\exp(-3.803) \times BW^{0.9072}]\} \quad \text{(Eq. 8-12)}$$

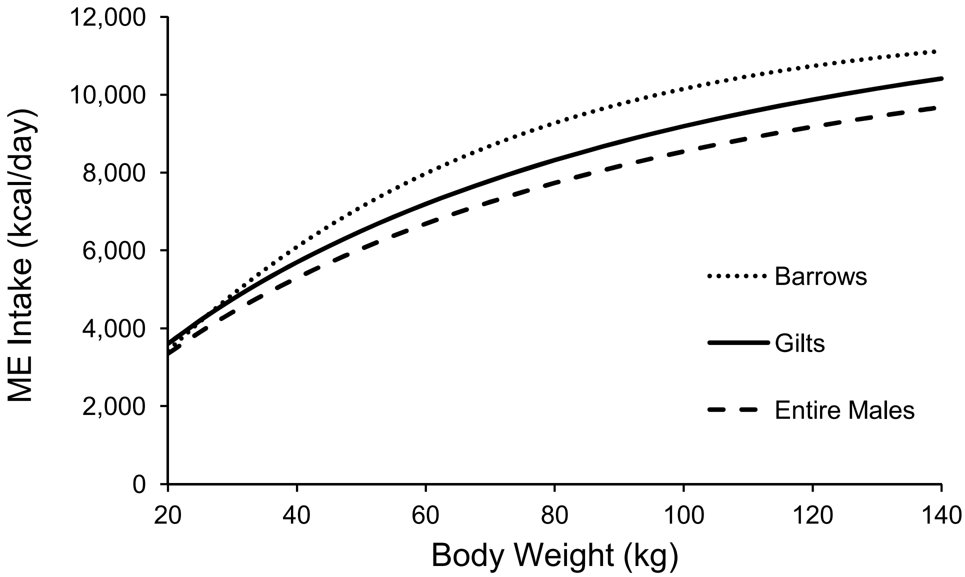

FIGURE 8-1 Typical daily ME intakes in barrows, gilts, and entire males between 20 and 140 kg body weight.

To represent the impact of effective environmental temperature (T) on ME intake (Bruce and Clark, 1979; Quiniou et al., 2000; Noblet et al., 2001), the lower critical temperatures (LCT) are estimated (Eq. 8-13). It is assumed that between the LCT and LCT + 3°C, T does not impact ME intake. At T above UCT + 3°C, ME intake decreases with increases in T (adjusted from Quiniou et al., 2000; Eq. 8-14). At T below LCT, ME intake increases linearly with T. The linear relationships between ME intake and T at T below LCT are defined for pigs at 25 and 90 kg BW, with linear adjustments for BW effects on the relationship between T and predicted ME intake. For pigs at 25 kg BW, predicted ME intake increases by 1.5% per degree Celsius below LCT. For pigs at 90 kg BW, predicted ME intake increases by 3% per degree Celsius below LCT.

$$\text{Lower critical temperature (LCT; °C)} = 17.9 - 0.0375 \times \text{BW} \qquad \text{(Eq. 8-13)}$$

$$\text{Fraction of ME intake} = 1 - 0.012914 \times [T - (\text{LCT} + 3)] - 0.001179 \times [T - (\text{LCT} + 3)]^2 \qquad \text{(Eq. 8-14)}$$

For predicting the impact of pig density on predicted ME intake, the minimum amount of space for maximum ME intake is calculated from BW (Eq. 8-15), while the predicted ME intake decreases by 0.252% per percent reduction in floor space (Gonyou et al., 2006).

$$\text{Minimum space for maximum ME intake } (m^2 / \text{pigs}) = 0.0336 \times \text{BW}^{0.667} \qquad \text{(Eq. 8-15)}$$

In particular, young growing pigs have limited physical capacity to ingest feed. If physical feed intake capacity is limiting, a reduction in dietary energy or nutrient content will not result in increased daily feed intake, as implied in Eqs. 8-9 to 8-12, and will lead to a reduction in daily nutrient intake. This concept is represented by a constraint on maximum daily feed intake as a function of BW (Black, 2009; Eq. 8-16). This equation also represents that physical feed intake capacity is increased when T is below LCT.

$$\text{Maximum daily feed intake (g/day)} = 111 \times \text{BW}^{0.803} + 111 \times \text{BW}^{0.803} \times (\text{LCT} - T) \times 0.025 \qquad \text{(Eq. 8-16)}$$

It has to be emphasized that this approach to predicting ME intake is highly empirical and fails to reflect the impact of environmental and animal factors that are known to influence energy intake, such as floor type, air quality and movement, pig genotype, and dietary levels of nutrients and antinutrients (e.g., Torrallardona and Roura, 2009). The application of the approach presented here is merely to demonstrate potential interactions between some environmental factors and estimated nutrient requirements, and to enable the user to quantitatively examine the effects of these factors on estimated nutrient requirements.

When an actual feed usage level (including feed wastage) and the corresponding mean BW is specified by the model user, the observed ME intake level is calculated considering diet ME content and feed wastage. The observed ME intake is calculated as a proportion of ME intake at that BW according to the reference ME intake curve. This proportion is then used to estimate ME intake at other BW.

Two types of mathematical equations (Bridges Eq. 8-17; polynomial Eq. 8-18) can be used to define ME intake curves as a function of BW (kg), with a, b, c, and d as parameters.

$$\text{Observed ME intake + wastage (kcal/day)} = a\,\{1 - \exp\,[-\exp\,(b) \times BW^{c}]\} \quad \text{(Eq. 8-17)}$$

$$\text{Observed ME intake + wastage (kcal/day)} = a + b \times BW + c \times BW^{2} + d \times BW^{3} \quad \text{(Eq. 8-18)}$$

Partitioning of ME Intake

In the model, the first priority is to satisfy maintenance energy requirements. The standard maintenance ME requirements are predicted from BW (kg; Eq. 8-19). If T is considered, the standard maintenance ME requirements increase linearly with reductions in T and when T is below LCT (Eq. 8-20).

$$\text{Standard maintenance ME requirements (kcal/day)} = 197 \times BW^{0.60} \quad \text{(Eq. 8-19)}$$

$$\text{ME requirements for thermogenesis (kcal/day)} = 0.07425 \times (LCT - T) \times \text{(standard maintenance ME requirements)} \quad \text{(Eq. 8-20)}$$

The model user can adjust maintenance energy requirements to account for variability in animal activity or genotype-specific effects by defining a proportional increase in standard maintenance ME requirements. The total maintenance ME requirements are then calculated (Eq. 8-21).

$$\text{Maintenance ME requirements (kcal/day)} = \text{standard maintenance ME requirements} + \text{ME requirements for thermogenesis} + \text{ME requirements for increased activity or genotype adjustment} \quad \text{(Eq. 8-21)}$$

Metabolizable energy intake in excess of maintenance ME requirements is used for Pd and Ld. The rate of Pd at a specific BW is determined by user-defined Pd curves or energy intake. Three alternative options are provided to define Pd curves: (1) enter a mean value for Pd between 25 and 125 kg BW, (2) specify parameters of mathematical equations relating either BP or Pd to BW, and (3) enter values for Pd_{Max} and the BW at which Pd_{Max} starts to decline.

For option (1), mean Pd is combined with a standard gender-specific Pd curve shape to derive Pd at specific BW (Eqs. 8-22, 8-23, 8-24). These standard curve shapes are a refinement of those presented in NRC (1998) and reflect typical effects of gender on growth patterns (e.g., Hendriks and Moughan, 1993; Wagner et al., 1999; BSAS, 2003; van Milgen et al., 2008; Schinckel et al., 2009a,b). Whole-body protein deposition curves that are based on these curve shapes and typical mean Pd values for the three genders (137, 133, and 151 g/day between 25 and 125 kg BW for gilts, barrows, and entire males, respectively) are presented in Figure 8-2.

$$\text{Pd, gilts (g/day)} = (137) \times (0.7066 + 0.013289 \times BW - 0.00013120 \times BW^{2} + 2.8627 \times 10^{-7} \times BW^{3}) \quad \text{(Eq. 8-22)}$$

$$\text{Pd, barrows (g/day)} = (133) \times (0.7078 + 0.013764 \times BW - 0.00014211 \times BW^{2} + 3.2698 \times 10^{-7} \times BW^{3}) \quad \text{(Eq. 8-23)}$$

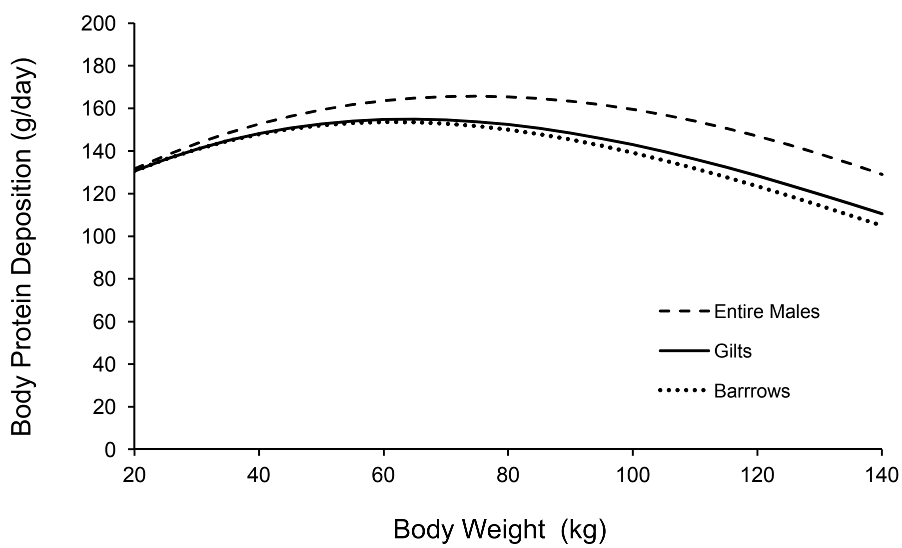

FIGURE 8-2 Typical whole-body protein deposition curves in entire males, gilts, and barrows between 20 and 140 kg body weight.

$$\text{Pd, entire males (g/day)} = (151) \times (0.6558 + 0.012740 \times BW - 0.00010390 \times BW^2 + 1.64001 \times 10^{-7} \times BW^3) \quad \text{(Eq. 8-24)}$$

For option (2), and when the generalized Michaelis-Menten kinetics function (Eq. 8-25) is used, daily Pd is calculated from BW changes, which requires that a BW gain curve is specified by the model user. The polynomial equation (Eq. 8-26) provides a direct relationship between Pd and BW.

$$\text{BP (kg)} = BP_{intial} + \{[(BP_{final} - BP_{initial}) \times (BW / a)^b] / [1 + BW / a)^b]\} \quad \text{(Eq. 8-25)}$$

$$\text{Pd (g/day)} = a + b \times BW + c \times BW^2 + d \times BW^3 \quad \text{(Eq. 8-26)}$$

In option (3), it is assumed that Pd_{Max} is constant and independent of BW until the BW at which Pd_{Max} starts to decline. In this option, it is thus assumed that as long as observed Pd is increasing with BW, Pd is determined by energy intake. At BW that is greater than the BW at which Pd_{Max} starts to decline, the Gompertz function is used to represent the pattern of decline in Pd with increasing BP (Eqs. 8-27, 8-28, and 8-29),

$$\text{BP at maturity (kg)} = (\text{BP at BW for } Pd_{Max} \text{ decline}) \times 2.7182 \quad \text{(Eq. 8-27)}$$

$$\text{Rate constant} = [Pd_{Max} / (\text{BP at maturity} \times 1{,}000)] \times 2.7182 \quad \text{(Eq. 8-28)}$$

$$\text{Maximum Pd after BW at which } Pd_{Max} \text{ starts to decline (g/day)} = (\text{BP at current BW}) \times 1{,}000 \times (\text{rate constant}) \times \ln(\text{BP at maturity / BP at current BW}). \quad \text{(Eq. 8-29)}$$

In the model, potential Pd as determined by energy intake is calculated for each day in the simulation (Eq. 8-30; adjusted from Black et al., 1986, and NRC, 1998). This equation yields linear relationships between energy intake and Pd, while the slope of this relationship decreases with increasing BW (Figure 8-3). This mathematical equation implies that when energy intake is extrapolated to maintenance energy intake, growing pigs gain body protein and mobilize body lipid. The latter is consistent with experimental observations (Black et al., 1986). The equation also represents greater slopes for pigs with greater lean tissue growth potentials and, when environmental temperature is considered, reductions in the slope with increases in environmental temperature. The model user has the ability to adjust this slope, using an adjustment factor, to match observed with predicted BW gains for specific groups of pigs. If Pd as determined by energy intake is smaller than the user-defined Pd, then the actual Pd is assumed to be equivalent to Pd as determined by energy intake. The latter applies to all three alternative options to define Pd curves.

$$\text{Pd as determined by energy intake (g/day)} = \{30 + [21 + 20 \times \exp(-0.021 \times BW)] \times (\text{ME intake} - 1.3 \times \text{maintenance ME requirements}) \times (Pd_{Max} \text{ or mean Pd} / 125) \times [1 + 0.015 \times (20 - T)]\} \times \text{adjustment} \quad \text{(Eq. 8-30)}$$

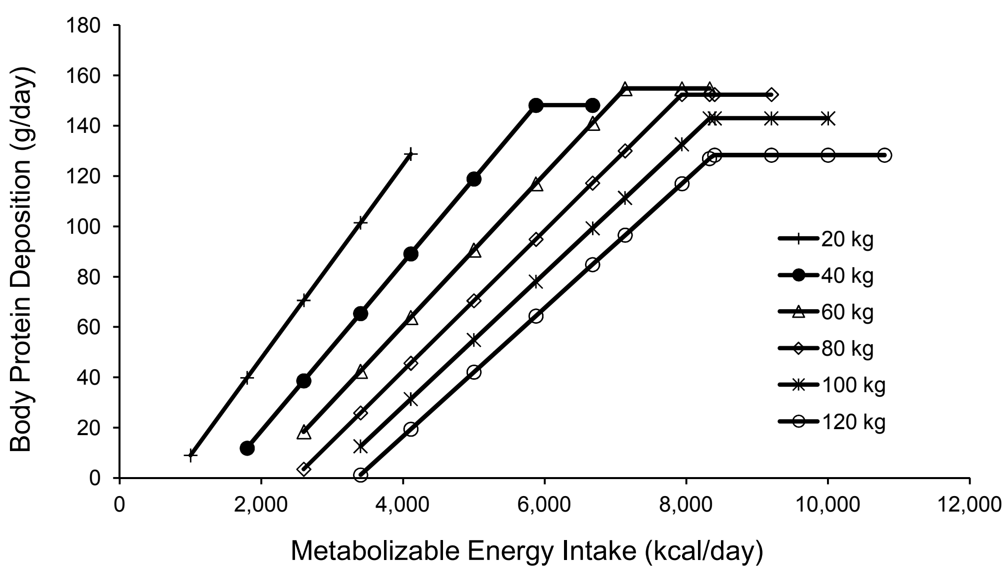

FIGURE 8-3 Relationship between whole-body protein deposition and metabolizable energy intake in gilts at various body weights and typical performance potentials.

TABLE 8-1 Model Estimated Typical Growth Performance of Gilts, Barrows, and Entire Male Pigs Between 20 and 130 kg BW[a]

Item	Gilts	Barrows	Entire Males
Predicted final body weight, kg	130.6	130.5	130.2
ME intake, kcal/day	6,825	7,345	6,583
Feed intake + feed wastage, g/day	2,177	2,343	2,100
Body weight gain, g/day	819	857	841
Whole-body protein deposition, g/day	132	130	143
Whole-body lipid deposition, g/day	234	277	207
Gain:(feed intake + feed wastage)	0.376	0.366	0.401
Probe backfat at final body weight, mm	17.5	20.9	14.3

[a]These estimates are based on the default ME intake curves (Eqs. 8-10 to 8-12; Figure 8-1) and Pd curves (Eqs. 8-22 to 8-24; Figure 8-2); diet ME content is 3,300 kcal/kg and feed wastage is 5%.

Once Pd has been established, Ld is calculated based on efficiencies of using ME intake over and above maintenance energy requirements for Pd and Ld (Eq. 8-31). The values 10.6 and 12.5 represent the ME cost of Pd and Ld, respectively (Chapter 1, Energy).

$$\text{Ld (g/day)} = (\text{ME intake} - \text{maintenance ME requirements} - \text{Pd} \times 10.6) / 12.5 \quad \text{(Eq. 8-31)}$$

Typical growth performance for the three genders of pigs is presented in Table 8-1. These levels of performance are based on the default ME intake curves (Eqs. 8-10 to 8-12; Figure 8-1) and Pd curves (Eqs. 8-22 to 8-24; Figure 8-2). In order to match simulated with observed growth performance and backfat thickness at the final BW, feed intake curves and Pd curves may be altered. In addition, the model user can alter maintenance energy requirements (Eq. 8-21) and the slope of the linear relationship between Pd and energy intake (Eq. 8-30).

Impacts of Feeding Ractopamine and Immunization of Entire Males Against Gonadotropin Releasing Hormone on Nutrient Partitioning

To represent the impact of feeding RAC on nutrient partitioning, calculation rules are adopted from the model described by Schinckel et al. (2006). In short, impacts of level and duration of feeding RAC on energy intake and Pd responses are considered, as well as the impact of RAC-induced Pd on the amino acid composition of Pd and body composition.

When feeding diets containing 20 mg/kg RAC, the proportional reduction in ME intake (MEIR) is assumed to be 0.036 of ME intake of untreated control pigs for the first 20 kg of BW gain on RAC (BWG_{RAC}). Thereafter, MEIR is gradually increased to approximately 0.078 of ME intake when BWG_{RAC} approaches 40 kg (Eq. 8-32).

$$\text{MEIR} = -0.191263 + (0.019013 \times BWG_{RAC}) - (0.000443 \times BWG_{RAC}^2) + (0.000003539 \times BWG_{RAC}^3) \quad \text{(Eq. 8-32)}$$

When feeding RAC levels that are lower than 20 mg/kg, ME intake (Mcal/day) is estimated according to Eq. 8-33.

$$\text{ME intake (kcal/day)} = \{1 - [\text{MEIR} \times (\text{diet RAC level} / 20)^{0.7})]\} \times \text{ME intake of untreated control pigs} \quad \text{(Eq. 8-33)}$$

The mean RAC-induced increase in predicted Pd over a 28-day feeding period is calculated as a proportion of Pd in untreated control pigs and based on a diminishing response to increasing diet RAC levels (Eq. 8-34; slightly adjusted from Schinckel et al., 2006). This equation predicts approximately 63 and 80% of the 20 mg/kg RAC response when dietary RAC levels are 5 and 10 mg/kg, respectively.

$$\text{Mean relative increase in RAC-induced Pd} = 0.33 \times (\text{diet RAC level} / 20)^{0.33} \quad \text{(Eq. 8-34)}$$

The mean relative RAC-induced Pd is adjusted for duration of feeding RAC, based on both BWG_{RAC} and days on RAC ($days_{RAC}$), as presented in Eqs. 8-35 and 8-36, with equal weighting for these two equations.

$$\text{Relative RAC-induced Pd} = 1.73 + (0.00776 \times BWG_{RAC}) - (0.00205 \times BWG_{RAC}^2) + (0.000017 \times BWG_{RAC}^3) + \{[(0.1 \times \text{diet RAC level}) - 1] \times (BWG_{RAC} \times 0.001875)\} \quad \text{(Eq. 8-35)}$$

$$\text{Relative RAC-induced Pd} = [1.714 + (0.01457 \times days_{RAC}) - (0.00361 \times days_{RAC}^2) + (0.000055 \times days_{RAC}^3)] \quad \text{(Eq. 8-36)}$$

To account for the response to diet RAC levels in step-up programs (i.e., when diet RAC levels are increased over time), the Pd response is adjusted based on the difference between the current diet RAC level (e.g., on day n) and the average diet RAC level over the period between 21 and 7 days prior to the current day (e.g., day n – 21 to day n – 7; Eq. 8-37).

$$\text{Relative increase in RAC-induced Pd in step-up programs)} = 6.73\ (\text{difference RAC diet level})^{0.50} / 100 \quad \text{(Eq. 8-37)}$$

In the model, RAC-induced Pd is tracked as a separate protein pool, which is an adjustment to the model described by Schinckel et al. (2006). This adjustment allows for representing the unique amino acid composition of RAC-induced Pd, RAC effect on requirements for all essential amino acids and N, as well as chemical and physical body composition (Eq. 8-38).

$$\text{RAC-induced fat-free lean tissue gain (g/day)} = \text{RAC-induced Pd} / 0.2 \quad \text{(Eq. 8-38)}$$

It is assumed that feeding RAC does not alter efficiencies of energy and amino acid utilization, including maintenance energy requirements, and that the response to RAC is not impacted by pig genotype and environmental conditions, per se.

The known impact of feeding RAC on the distribution of body lipid over the various body fat pools is represented by the impact of RAC probe backfat thickness (Eq. 8-39). In this equation, days_{RAC} cannot exceed 10, implying that a 10-day adjustment is required to reach the full impact of feeding RAC on backfat thickness. At the 20-mg/kg diet RAC level, predicted probe backfat thickness increases 5%.

$$\text{Probe backfat thickness, adjusted for RAC (mm)} = \text{Probe backfat thickness} \times (1 + 0.05 \times \text{days RAC} / 10) \times (\text{diet RAC level} / 20)^{0.7} \quad \text{(Eq. 8-39)}$$

At the time that this publication was prepared, no meaningful empirical studies were available to determine the impact of immunization of entire males against GnRH on nutrient requirements. However, based on reverse modeling of typical responses in energy intake, BW gains and changes in estimated chemical body composition during a 4- to 5-week period following the second injection for immunization against GnRH with Improvest™ (Chapter 1 Energy), estimates of nutrient requirements were generated. It was estimated that after a transition period, immunization increases energy intake by 21%, reduces maintenance energy requirements by 12%, and reduces Pd by 8%. Moreover and based on daily changes in feed intake, it was assumed that there is a 10-day gradual transition period after the second injection and to transform the entire male to a male immunized against GnRH. For the estimation of nutrient requirements, it was assumed that immunization of entire males against GnRH does not impact efficiencies of energy and amino acid utilization for the main body functions and that the response to this immunization is not impacted by pig genotype and environmental conditions. In these calculations, the impact of immunization against GnRH on gut fill is not considered; also, its effect on gut fill and carcass dressing percentage has to be considered when calculating fat-free lean gain from live BW at slaughter (e.g., Pauly et al., 2009).

Amino Acid Requirements

As outlined in Chapter 2 (Proteins and Amino Acids), the modeling approach to estimate requirements for essential amino acids and N has been adjusted from Moughan (1999). The main determinants of amino acid and N requirements that are considered in the model are (1) basal endogenous gastrointestinal tract (GIT) losses, which are related to feed intake; (2) integument losses, as a function of kg $BW^{0.75}$; (3) Pd; and (4) the efficiency of using SID amino acid intake for the three aforementioned functions. The inefficiency of amino acid utilization reflects minimum plus inevitable amino acid catabolism and between-animal variability in Pd. Primarily due to between-animal variability in feed intake and Pd, the efficiency of amino acid utilization is lower in groups of pigs than in individual pigs (Pomar et al., 2003).

Here the calculations are presented for lysine requirements. Based on the optimum ratio among amino acids for supporting the main body functions and estimates of the efficiency of amino acid utilization, requirements for the other essential amino acids (Table 2-12) and total N are estimated.

Basal endogenous lysine losses recovered at the terminal ileum have been estimated at 0.417 g per kilogram of feed dry matter intake; these losses have been related to feed intake, assuming 88% feed dry matter, and to whole-GIT losses, assuming that large intestinal losses represent 10% of GIT losses recovered at the ileum (Eq. 8-40). Integument lysine losses have been estimated at 4.5 mg per kilogram of $BW^{0.75}$ (Eq. 8-41).

$$\text{Basal endogenous GIT lysine losses (g/day)} = \text{feed intake} \times (0.417 / 1{,}000) \times 0.88 \times 1.1 \quad \text{(Eq. 8-40)}$$

$$\text{Integument lysine losses (g/day)} = 0.0045 \times BW^{0.75} \quad \text{(Eq. 8-41)}$$

To estimate the SID lysine requirements for these two body functions, an estimate of minimum plus inevitable lysine catabolism is used (Eq. 8-42), which is a deviation from the approach that was suggested by Moughan (1999). Inevitable plus minimum lysine catabolism is assumed to be 25% of SID lysine intake, equivalent to a 0.75 efficiency of SID lysine utilization to support basal GIT lysine losses and integument lysine losses. This inevitable plus minimum catabolism value is derived from observations on individual pigs and in well-controlled serial slaughter studies conducted between approximately 30 and 70 kg BW (Bikker et al., 1994; Moehn et al., 2000). This efficiency appears independent of BW and increases with improvements in pig performance potential. For every 1-g increase in maximum Pd, relative to the typical mean value for gilts and barrows, the rate of minimum plus inevitable lysine catabolism is reduced by 0.002 (Moehn et al., 2004).

$$\text{SID lysine requirements for GIT plus integument losses (g/day)} = (\text{Eq. 8-40} + \text{Eq. 8-41}) / (0.75 + 0.002 \times (\text{maximum Pd} - 147.7) \quad \text{(Eq. 8-42)}$$

It is assumed that Pd contains 7.10% lysine while RAC-induced Pd is assumed to contain 8.22% lysine (Chapter 2; Eq. 8-43).

$$\text{Lysine retained in Pd (g/day)} = \text{Non-RAC-induced Pd} \times 7.10 / 100 + \text{RAC-induced Pd} \times 8.22 / 100 \quad \text{(Eq. 8-43)}$$

To account for between-animal variability, the marginal efficiency of utilizing SID lysine intake above maintenance requirements for lysine retention was reduced (from 0.75) and adjusted to match estimated with determined SID lysine requirements in empirical lysine requirement studies, as outlined in Chapter 2 (Proteins and Amino Acids). These analyses revealed that the marginal efficiency of lysine utilization declines with BW. This efficiency was estimated at 0.682 at 20 kg BW (equivalent to an increase in lysine requirements for Pd of 9.9%) and 0.568 at 120 kg BW (equivalent to an increase in lysine requirements for Pd of 32.05%), and extrapolated to other BW based on a linear relationship with BW. Based on the aforementioned lysine content in Pd, these efficiencies are equivalent to 10.4 and 12.5 g SID lysine requirements per 100 g Pd at 20 and 120 kg BW, respectively, for pigs that are not fed RAC and with a maximum Pd of 147.7 g/day. Standardized ileal digestible ID lysine requirements for Pd and total daily SID lysine requirements are then calculated based on Eqs. 8-44 and 8-45. Gender-specific SID lysine requirement curves are shown in Figure 8-4.

$$\text{SID lysine requirements for Pd (g/day)} = \{\text{Lysine retained in Pd} / [0.75 + 0.002 \times (\text{maximum Pd} - 147.7)]\} \times (1 + 0.0547 + 0.002215 \times \text{BW}) \quad \text{(Eq. 8-44)}$$

$$\text{Total SID lysine requirements (g/day)} = \text{requirements for gut plus integument losses} + \text{requirements for Pd} \quad \text{(Eq. 8-45)}$$

The above calculations were applied to all other essential amino acids and total N, based on their ratio to lysine for each of the determinants of amino acid requirements (Chapter 2; Tables 2-5 to 2-12). The absolute rates of minimum plus inevitable catabolism (e.g., the value 0.75 in Eqs. 8-43 and 8-44) were adjusted for individual amino acids to match model-generated estimates of SID amino acid requirements with empirical estimates of amino acid requirements (Chapter 2, Proteins and Amino Acids). For several amino acids, no empirical estimates of requirements were available (e.g., leucine, phenylalanine, phenylalanine plus tyrosine). In these cases, absolute rates of minimum plus inevitable catabolism were adjusted to match model-generated requirements with requirements presented in NRC (1998) for growing pigs with typical performance levels and at 65 kg BW. For histidine, the rate of minimum plus inevitable catabolism was set at 1, which yields estimates of SID histidine requirements that exceeded requirements according to NRC (1998). For arginine, the rate of minimum plus inevitable catabolism was set at 1.47, implying some endogenous arginine synthesis.

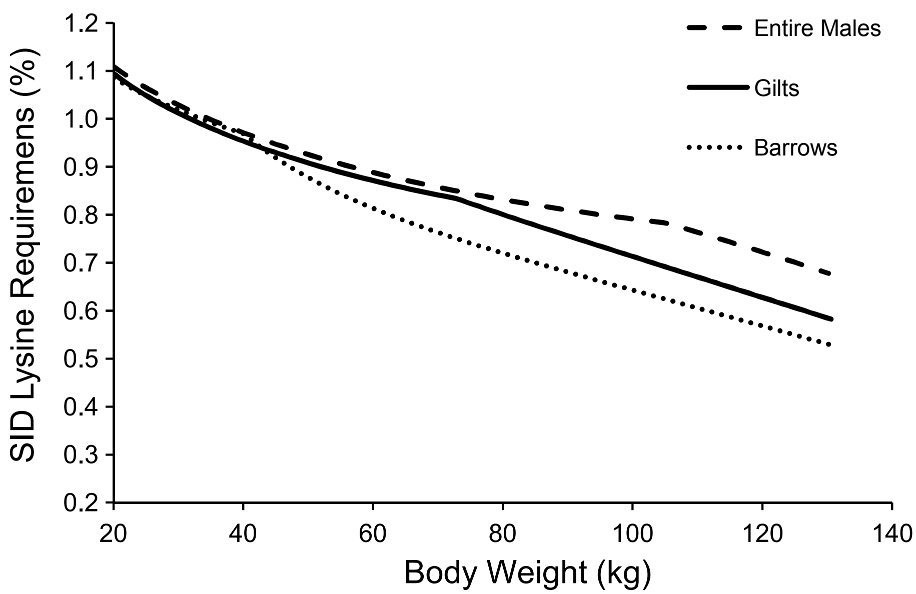

FIGURE 8-4 Simulated SID lysine requirements (g/kg of diet) of entire males, gilts, and barrows between 20 and 130 kg body weight.

The only additional calculation rule is the fermentative SID threonine losses (Eq. 8-46), as a function of daily fermentable fiber content (Chapter 2, Proteins and Amino Acids; Zhu et al., 2005).

$$\text{Fermentative SID threonine losses (g/day)} = (\text{feed intake} / 1{,}000) \times \text{diet fermentable fiber content} \times (4.2 / 1{,}000) \quad \text{(Eq. 8-46)}$$

Calcium and Phosphorus Requirements

Factorial estimates of requirements for STTD P and total Ca are adjusted from Jongbloed et al. (1999) and Jondreville and Dourmad (2005), as outlined in Chapter 6 (Minerals). The contributors to STTD P requirements are (1) maximum P retention rates in the body, as a function of changes in BP; (2) basal endogenous GIT P losses, as a function of feed dry matter intake; (3) minimum urinary P losses, as a function of BW; (4) marginal efficiency of using STTD P intake for P retention; and (5) P requirements for maximum growth performance as a proportion of P requirements for maximum whole-body P retention. Calcium requirements are derived directly from STTD P requirements.

In order to account for some of the pig genotype and gender effects on P requirements, whole-body P mass is related directly to BP (Eq. 8-47; BP expressed in kg; Chapter 6, Minerals, Figure 6-1). It is assumed that feeding RAC or immunizing entire males against GnRH does not impact the relationship between whole-body P mass and BP.

$$\text{Body P mass (g)} = 1.1613 + 26.012 \times \text{BP} + 0.2299 \times \text{BP}^2 \quad \text{(Eq. 8-47)}$$

The basal endogenous GIT P losses are estimated at 190 mg/kg feed dry matter intake, while minimum urinary losses are assumed to be 7 mg/kg BW per day (Chapter 6, Minerals). The marginal efficiency of using STTD P intake for whole-body P retention is assumed to be 0.77; the marginal inefficiency reflects the increase in both endogenous urinary and fecal P losses with increases in STTD P intake and when P intake is approaching requirements for maximum P retention, and likely reflects metabolic inefficiencies, as well as between-animal variability (Chapter 6, Minerals). In the model, it is assumed that P requirements for maximum growth performance are equivalent to 0.85 (Chapter 6, Minerals) of P requirements for maximum whole-body P retention (Eq. 8-48).

$$\text{STTD P requirements (g/day)} = 0.85 \times [(\text{maximum whole-body P retention}) / 0.77 + 0.19 \times \text{feed dry matter intake} + 0.007 \times \text{BW}] \quad \text{(Eq. 8-48)}$$

A fixed ratio of 2.15 is used to calculate Ca requirements from STTD P requirements (Chapter 6, Minerals).

In establishing these requirements, it is assumed that there is no dietary imbalance between macrominerals and in particular between Ca and P. It has been well documented that excess Ca intake will reduce the efficiency of P utilization and increase dietary P requirements. This is discussed in further detail in Chapter 6 (Minerals). The impact of using phytase on estimates of STTD P and Ca requirements is not considered. It is thus assumed that phytase will affect P digestibility only and not the aforementioned contributors to STTD P and Ca requirements.

GESTATING SOW MODEL

Main Concepts

The model described by Dourmad et al. (1999, 2008) served as a basis for the gestation model. Daily energy intake has to be defined by the model user and can be varied at different periods during gestation. Weight, protein, and energy gain of conceptus (fetuses, placenta plus uterine fluids) are represented explicitly and as a function of anticipated litter size at birth, mean piglet birth weight, and time. Weight and energy gains of the empty uterus and mammary tissue are considered part of the maternal body. In the model, six different protein pools are identified: fetus, placenta plus fluids, uterus, mammary tissue, time-dependent maternal Pd, and energy intake-dependent maternal Pd, which is a deviation from Dourmad et al. (1999, 2008) and described in detail in Chapter 2 (Proteins and Amino Acids). In the model, it is assumed that energy intake-dependent maternal Pd increases linearly with energy intake, while this response is assumed to vary with parity and to be identical at all stages of gestation. Energy intake that is not used for body maintenance functions, growth of conceptus, and Pd in the maternal body (including uterus and mammary gland) is used for maternal Ld. When energy intake is insufficient to support body maintenance functions, gain of conceptus, and Pd in the maternal body, maternal body lipid is mobilized and used as a source of energy. Maternal BW change is predicted from daily changes in maternal body BP (excluding conceptus, but including uterus and mammary gland) and maternal BL. The P2 backfat measurement is used as an estimate of body fatness. The SID amino acid requirements are estimated from protein gain in the six different pools, BW, and feed intake. The STTD P requirements are derived from feed intake, BW, gains of maternal BW and conceptus, and a parity-dependent rate of P requirement for bone (re-)mineralization. Total Ca requirements are estimated from STTD P requirements.

Body Composition

Body composition is represented mathematically according to Dourmad et al. (1999, 2008). Total BW (kg) represents the sum of maternal BW and the weight of the conceptus. The difference between maternal BW and maternal EBW is equivalent to gut fill, which is assumed to represent 4% of maternal BW (Eq. 8-49). The EBW and P2 backfat are used to generate estimates of maternal BL and maternal BP at the start of gestation (Eqs. 8-50 and 8-51). In the dynamic simulations, maternal BL and maternal BP are tracked and used to predict EBW (Eq. 8-52), P2 backfat (Eq. 8-53), and daily changes in total BW.

$$\text{Maternal EBW (kg)} = 0.96 \times \text{maternal BW} \quad \text{(Eq. 8-49)}$$

$$\text{Maternal BL (kg)} = -26.4 + 0.221 \times \text{maternal EBW} + 1.331 \times \text{P2 backfat} \quad \text{(Eq. 8-50)}$$

$$\text{Maternal BP (kg)} = 2.28 + 0.178 \times \text{maternal EBW} - 0.333 \times \text{P2 backfat} \quad \text{(Eq. 8-51)}$$

$$\text{Maternal EBW (kg)} = 119.457 + 4.5249 \times \text{maternal BP} - 6.0226 \times \text{maternal BL} \quad \text{(Eq. 8-52)}$$

$$\text{P2 backfat (mm)} = 16.76 - 0.7117 \times \text{maternal BP} + 0.5732 \times \text{maternal body BL} \quad \text{(Eq. 8-53)}$$

Growth of Conceptus and Protein Pools

The weight and energy content of conceptus are estimated using natural logarithmic values and as a function of time (t, days into gestation) and anticipated litter size at farrowing (ls, total number of pigs born) (Eqs. 8-54 and 8-55; Dourmad et al., 1999, 2008). The protein content of the fetus is estimated in a similar manner (Eq. 8-56), while the protein content in placenta plus fluids is represented as a function of time and anticipated litter size, but using a Michaelis-Menton kinetics function (Eq. 8-57), based on data summarized in Chapter 2 (Proteins and Amino Acids). Daily weight, protein, or energy gains of conceptus are calculated as the difference between values on subsequent days (t = n vs. t = n + 1).

$$\text{Weight of conceptus (g)} = \exp(8.621 - 21.02 \times \exp(-0.053 \times t) + 0.114 \times ls) \quad \text{(Eq. 8-54)}$$

$$\text{Energy content of conceptus (kcal)} = \{\exp[11.72 - 8.62 \times \exp(-0.0138 \times t) + 0.0932 \times ls]\} / 4.184 \quad \text{(Eq. 8-55)}$$

$$\text{Protein content of fetus (g)} = \exp[8.729 - 12.5435 \times \exp(-0.0145 \times t) + 0.0867 \times ls] \quad \text{(Eq. 8-56)}$$

$$\text{Protein content of placenta plus fluids (g)} = [(38.54) \times (t / 54.969)^{7.5036}] / [1 + (t / 54.969)^{7.5036}] \quad \text{(Eq. 8-57)}$$

These four entities are corrected for mean piglet birth weight, based on the ratio between actual litter weight at birth and the anticipated litter birth weight based on anticipated gestation length and litter size (Ratio, Eq. 8-58; assuming 114-day gestation period).

$$\text{Ratio} = (ls \times \text{average piglet birth weight, g}) / 1.12 \times \exp\{[9.095 - 17.69 \exp(-0.0305 \times 114) + 0.0878 \times ls]\} \quad \text{(Eq. 8-58)}$$

In these calculations, it is assumed that energy intake does not impact growth of conceptus, which is consistent with the observation that growth of conceptus is reduced only at severe energy intake restrictions (Dourmad et al., 1999).

Protein contents of uterus and mammary are estimated using natural logarithmic values and as a function of time (Eqs. 8-59 and 8-60), based on data summarized in Chapter 2 (Proteins and Amino Acids).

$$\text{Protein content of uterus (g)} = \exp[6.6361 - 2.4132 \times \exp(-0.0101 \times t)] \quad \text{(Eq. 8-59)}$$

$$\text{Protein content of mammary tissue (g)} = \exp\{8.4827 - 7.1786 \times \exp[-0.0153 \times (t - 29.18)]\} \quad \text{(Eq. 8-60)}$$

Time-dependent maternal body protein gain represents residual protein retention observed in N balance studies that cannot be attributed to any of the other protein pools. As protein gain in this pool only occurs during the first part of gestation, a protein gain value of 0 is forced after day 56 of gestation, and protein gain is predicted using a Michaelis-Menton kinetics function (Eq. 8-61).

$$\text{Time-dependent maternal body protein content (g)} = \{[(1522.48) \times (56 - t) / 36]^{2.2}\} / \{1 + [(56 - t) / 36]^{2.2}\} \quad \text{(Eq. 8-61)}$$

Maternal Pd that is dependent on daily energy intake is related linearly to ME intake above maintenance ME requirements on day 1 of gestation (Eq. 8-62), while the slope (a) declines with increasing parity (par) and cannot be lower than 0 (Eq. 8-63). This slope was adjusted from Dourmad et al. (2008) and varied across parity to achieve a reasonable fit between observed and estimated changes in the sow's body composition across parities (see section Evaluation of the

Models in this chapter). The model user can adjust the slope of this linear relationship to match observed with predicted sow BW changes and changes in backfat thickness. Patterns of Pd for the various pools are presented in Figures 2-1 and 2-2 and summarized in Figure 8-5.

$$\text{Maternal Pd that is dependent on energy intake (g/day)} = a \times (\text{ME intake} - \text{maintenance ME requirements on day 1 of gestation, kcal/day}) \times \text{adjustment} \quad \text{(Eq. 8-62)}$$

$$\text{Coefficient a in Eq. 8-62} = (2.75 - 0.5 \times \text{par}) \times \text{adjustment};\ a > 0 \quad \text{(Eq. 8-63)}$$

Partitioning of ME Intake

In the model, priority is given to satisfy energy requirements for body maintenance functions, growth of conceptus, and maternal Pd (including Pd in uterus and mammary tissue). The standard maintenance energy requirements are calculated as a function of total BW (kg; Eq. 8-64). The impacts of gestating sow activity level and the thermal environment on maintenance energy requirements are represented as well. In addition, the model user can make adjustments to account for additional situation-specific maintenance energy requirements.

$$\text{Standard maintenance ME requirements (kcal/day)} = 100 \times (\text{total BW})^{0.75} \quad \text{(Eq. 8-64)}$$

If sows are known to spend more than 4 hours per day standing, then the maintenance ME requirements are increased by 0.0717 kcal/day per kg total $BW^{0.75}$ per minute additional standing time (Dourmad et al., 2008). In the model, it is assumed that the LCT is 20 and 16°C for individually and group-housed sows, respectively. For group-housed sows that are kept on straw, the LCT is reduced by an additional 4°C (Bruce and Clark, 1979). The additional maintenance ME requirements are increased by 4.30 and 2.39 kcal/day per degree Celsius below LCT and per kilogram total $BW^{0.75}$ for individually and group-housed sows, respectively.

Energy intake that is not used for body maintenance functions, growth of products of conceptus, and maternal Pd is used for maternal Ld (Eq. 8-65; energy in kcal; Chapter 1, Energy). If energy intake is insufficient to support maintenance ME requirements, growth of conceptus, and maternal Pd, then maternal BL is mobilized and used as a source of ME with an energetic efficiency of 0.80.

$$\text{Maternal Ld (g/day)} = (\text{ME intake} - \text{maintenance ME requirements} - \text{energy retention in conceptus} / 0.5 - \text{maternal Pd} \times 10.6) / (12.5) \quad \text{(Eq. 8-65)}$$

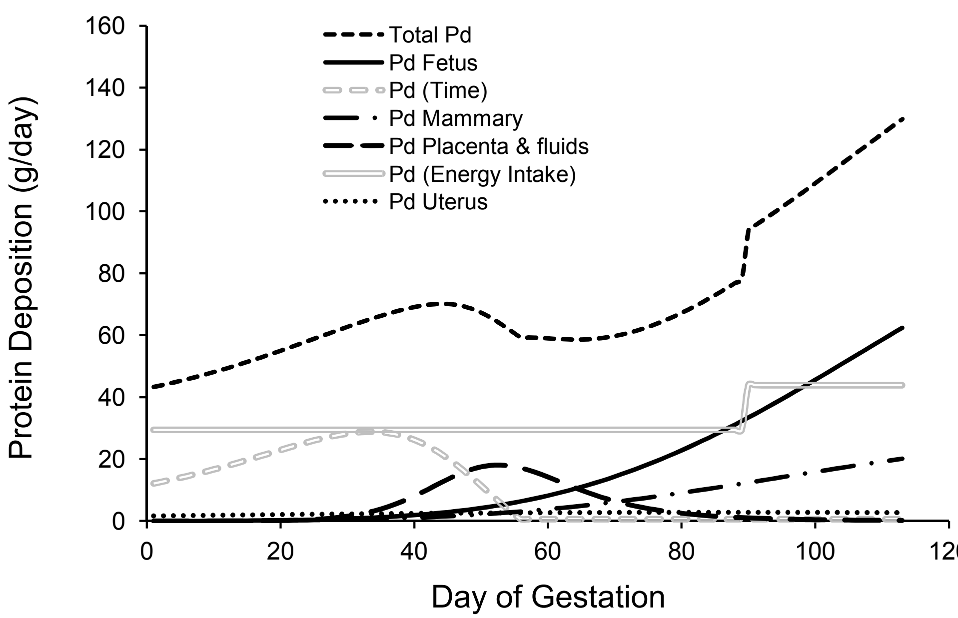

FIGURE 8-5 Typical protein deposition (Pd) patterns for fetus, mammary tissue, placenta and fluids, maternal protein as a function of time, and maternal protein as a function of energy intake during gestation in parity-2 sows based on an anticipated litter size of 13.5 piglets and a mean birth weight of 1.4 kg.

Amino Acid Requirements

The main determinants of amino acid requirements that are considered in the gestating sow model include (1) basal endogenous GIT losses, which are related to feed intake; (2) integument losses, as a function of kilograms of $BW^{0.75}$; (3) protein gain in the six different protein pools; and (4) the efficiency of using SID amino acid intake for the aforementioned functions. Basal endogenous GIT losses, integumental losses, and efficiency of using SID amino acid were adjusted from those in the growing-finishing pig model.

The approach to calculate SID lysine requirements to cover endogenous gut lysine losses and integument lysine losses is identical to those for growing-finishing pigs (Eqs. 8-40 to 8-42), except that the GIT lysine losses per kilogram of feed intake were assumed to be 0.5053 g and no adjustment is made in Eq. 8-42 for pig performance potential (Chapter 2, Proteins and Amino Acids). The SID lysine requirements for lysine retention reflects the lysine content in gain of the six protein pools, as well as minimum plus inevitable lysine catabolism and an adjustment to account for between-animal variability (Eq. 8-66; Chapter 2, Proteins and Amino Acids), which is an adjustment from Eq. 8-44. Total SID lysine requirements represent the sum of SID lysine requirements to cover endogenous gut lysine losses and integument lysine losses and SID lysine requirements for lysine retention. Changes in SID lysine requirements (g/day) during gestation are shown in Figure 8-6.

$$\text{SID lysine requirements for lysine retention (g/day)} = [(\text{Total lysine retention}) / 0.75] \times 1.589 \qquad \text{(Eq. 8-66)}$$

The above calculations were applied to all other essential amino acids and total N, based on their ratio to lysine for each of the determinants of amino acid requirements (Chapter 2, Tables 2-5 and 2-11). For amino acids other than lysine, no requirement studies have been reported that met the criteria outlined in Chapter 2 (Proteins and Amino Acids). The absolute rates of minimum plus inevitable catabolism (e.g., the value 0.75 in Eq. 8-66; Table 2-12) were forced to match model-generated requirements to requirements presented in NRC (1998) for gestating sows (parity-3 sow with initial BW 175 kg). For tryptophan and valine, this parameter was deemed too high (0.752 and 0.934, respectively), relative to the estimate of minimum plus inevitable catabolism used in the growing-finishing pig model; in a similar manner for isoleucine, this parameter was deemed too low. Therefore, for tryptophan, valine, and isoleucine, additional adjustments were made to the estimates of minimum plus inevitable catabolism. These adjustments reflect the fact that the contents of tryptophan, valine, and isoleucine differ substantially in conceptus, mammary tissue, and uterus pools compared to these in maternal body protein pool, and these amino acid profiles were not available for NRC (1998). For N, a value of

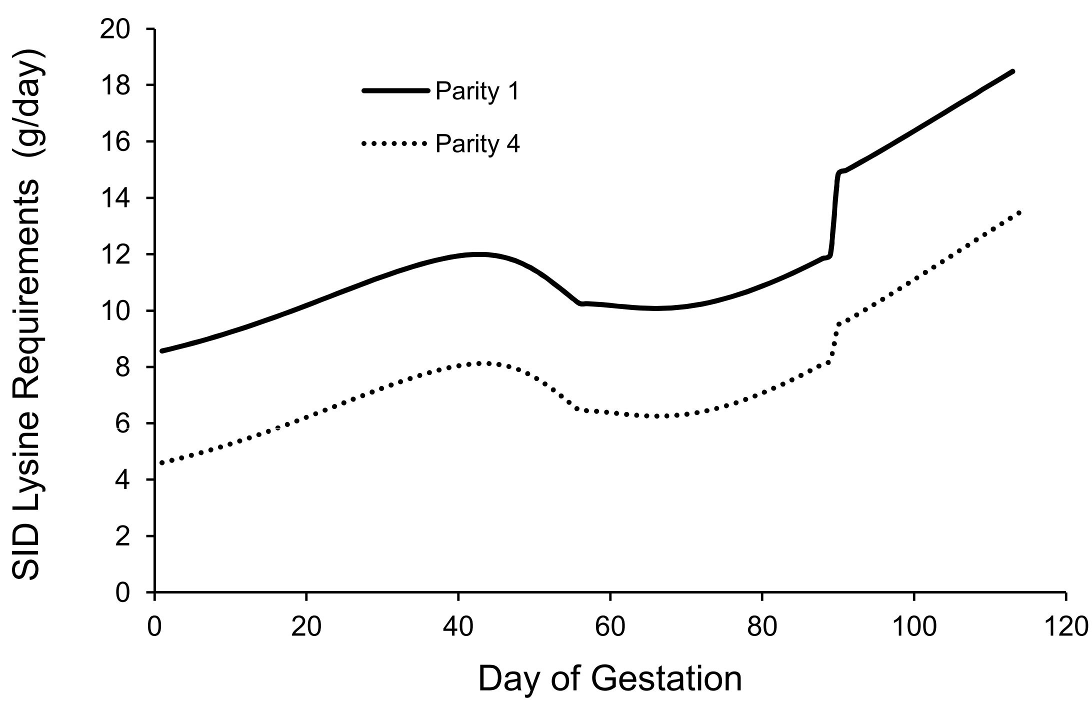

FIGURE 8-6 Simulated SID lysine requirements (g/day) of primiparous (body weight at mating 140 kg; anticipated total gain 65 kg; mean litter size 12.5; mean piglet birth weight 1.4 kg) and parity-4 (body weight at mating 205 kg; anticipated total gain 45 kg; mean litter size 13.5; mean piglet birth weight 1.4 kg) gestating sows.

0.85 was used, identical to the value in the growing-finishing pig model (Table 2-12).

Calcium and Phosphorus Requirements

The general approach used to estimate requirements for STTD P is similar to that for growing-finishing pigs (Chapter 6, Minerals), and reflects (1) P retention in the maternal body and conceptus, (2) basal endogenous gut P losses (190 mg/kg feed dry matter intake), (3) minimum urinary P losses (7 mg per kg BW), and (4) marginal efficiency of using STTD P intake for P retention (0.77).

Phosphorus mass in conceptus (fetuses and placenta) is represented according to Jongbloed et al. (1999), which is consistent with the approach used by Jondreville and Dourmad (2005). Phosphorus mass in fetuses is calculated as a function of time and litter size (Eq. 8-67). Phosphorus mass in placenta plus fluids is estimated from its protein content (Eq. 8-68) and based on P to protein ratio of 0.0096 (Jongbloed et al., 1999). Phosphorus content in both fetuses and placenta plus fluids are adjusted for piglet birth weights, as is the case for other products of conceptus (Eq. 8-58).

$$\text{P content of fetuses (g)} = \exp\{4.591 - 6.389 \times \exp[-0.02398 \times (t - 45)] + (0.0897 \times ls)\} \quad \text{(Eq. 8-67)}$$

$$\text{P content of placenta (g)} = 0.096 \times \text{Protein content of placenta and fluids} \quad \text{(Eq. 8-68)}$$

Phosphorus retention in the maternal body, including the empty uterus and mammary tissue, is calculated from maternal Pd and a parity-dependent daily P retention in bone tissue (2.0, 1.6, 1.2, and 0.8 g/day for parity 1, 2, 3, and 4 and up, respectively), adjusted from Jongbloed et al. (1999; Eq. 8-69). A fixed ratio of 2.30 is used to calculate Ca requirements from STTD P requirements (Chapter 6, Minerals).

$$\text{Phosphorus retention in the maternal body (g/day)} = 0.0096 \times \text{Pd in the maternal body} + \text{parity-dependent daily P retention in bone tissue} \quad \text{(Eq. 8-69)}$$

LACTATING SOW MODEL

Main Concepts

The lactating sow model has been adjusted from the model described by Dourmad et al. (2008). Daily energy intake can be predicted from parity and days into lactation or defined by the model user. Daily milk energy and milk protein output are predicted from litter size, mean piglet growth rate over the entire lactation period, and a standard milk production curve shape. Energy intake that is not used for body maintenance functions and milk production is used for maternal Ld and Pd. When energy intake is insufficient to support maintenance energy requirements and milk production, then both maternal BL and BP are mobilized and used as sources of energy. Maternal BW change is predicted from daily changes in maternal BP and maternal BL. The P2 backfat measurement is used as an estimate of body fatness. The SID amino acid requirements are estimated from litter growth rate, changes in maternal BP, BW, and feed intake. The STTD P requirements are derived from feed intake, BW, litter growth rate, and changes in maternal BW, while total Ca requirements are estimated from STTD P requirements.

Body Composition

The representation of body composition in lactating sows is identical to that described for gestating sows.

Milk Production

Mean daily milk energy and N output are predicted from mean daily litter gain and litter size (Eqs. 8-70 and 8-71) based on Dourmad et al. (1999, 2008). These mean values are converted to milk energy and N output on specific days, using a standard lactation curve shape (Eq. 8-72). Daily milk production is calculated from milk N output and assuming that milk contains 8.0 g N/kg (Chapter 2).

$$\text{Mean milk energy output (kcal/day)} = 4.92 \times \text{mean litter gain (g/day)} - 90 \times ls \quad \text{(Eq. 8-70)}$$

$$\text{Mean milk N output (g/day)} = 0.0257 \times \text{mean litter gain (g/day)} + 0.42 \times ls \quad \text{(Eq. 8-71)}$$

$$\text{Milk Energy or N output on day } t = \text{Mean output} \times (2.763 - 0.014 \times \text{lactation length}) \times \exp(-0.025 \times t) \times \exp[-\exp(0.5 - 0.1 \times t)] \quad \text{(Eq. 8-72)}$$

Partitioning of ME Intake

Daily intake of ME can be defined by the model user or predicted from day into lactation (Eq. 8-73; adjusted downward by 7.5% from Schinckel et al. (2010a) to achieve a mean daily intake of 20.5 Mcal/day of ME over a 20-day lactation period). For first-parity sows, predicted ME intake is reduced by 10% (Figure 8-7) (Schinckel et al., 2010a). Moreover, it is assumed that per degree Celsius increase in temperature above UCT (22°C), daily ME intake is reduced (1.6% per Celsius degree per day for 22-25ºC; 3.67% per Celsius degree per day above 25ºC; Chapter 1 [Energy]).

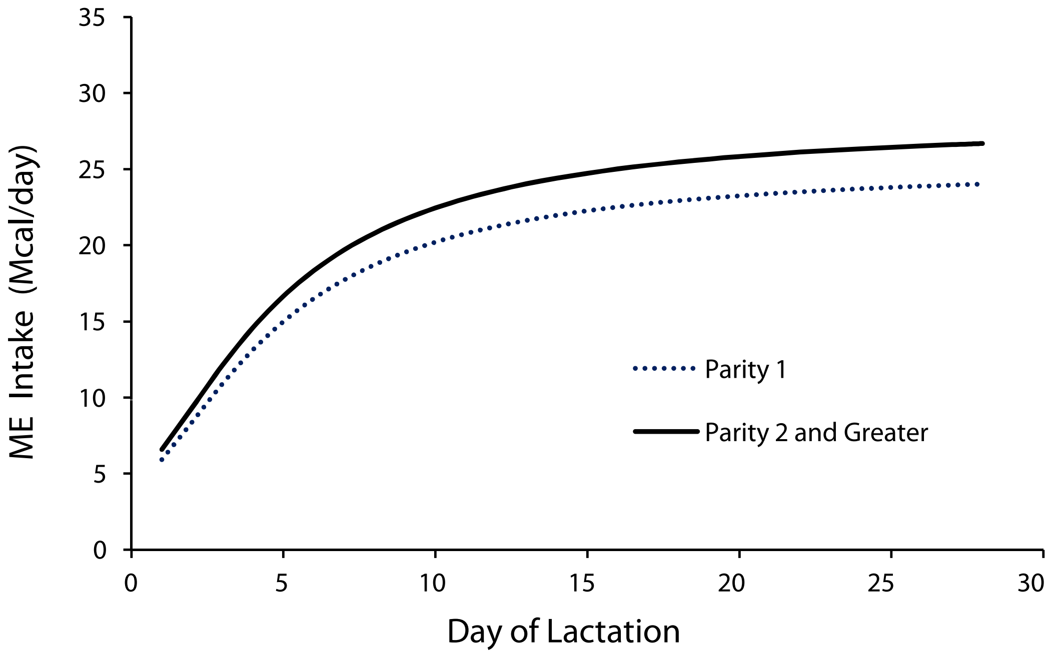

FIGURE 8-7 Typical daily metabolizable energy intake in primiparous and multiparous sows.

$$\text{Predicted ME intake in multiparous sows (kcal/day)} = 4{,}921 + \{[(28{,}000 - 4{,}921) \times (\text{day} / 4.898)^{1.612}] / [1 + (\text{day} / 4.898)^{1.612}]\} \quad \text{(Eq. 8-73)}$$

In the model, priority is given to satisfy maintenance energy requirements (Eq. 8-74) and energy requirements for milk production (Eq. 8-75). In the model it is assumed that milk production is not sensitive to energy intake.

$$\text{Standard ME maintenance requirements (kcal/day)} = 100 \times (\text{BW, kg})^{0.75} \quad \text{(Eq. 8-74)}$$

$$\text{ME requirements for milk production (kcal/day)} = (\text{Milk energy output, kcal/day}) / 0.70 \quad \text{(Eq. 8-75)}$$

If ME intake exceeds requirements for maintenance and milk production, then it is assumed that sows gain both body lipid and body protein, requiring 10.6 and 12.5 kcal ME per g Ld and Pd, respectively. In most instances, ME intake is insufficient to meet requirements for maintenance and milk production. In that case, the energetic efficiency of utilizing body energy reserves for milk energy output is assumed to be 0.87. The default ratio for the relative contribution of energy from BP and BL to changes in body energy content is 0.12, which is equivalent to a body protein content of 10% in maternal BW changes (Chapter 2, Proteins and Amino Acids). This ratio was derived from a review of published data on changes in sow BW and backfat during lactation and based on changes in body composition that were estimated with Eqs. 8-49 to 8-51; the ratio was deemed identical for sows in a positive vs. sows in a negative body energy balance. The default ratio can be adjusted by the model user to match observed with predicted BW and backfat thickness changes during lactation.

Amino Acid Requirements

Requirements for the essential amino acids and N are derived from the optimum ratios among amino acids for supporting the main body functions and estimates of amino acid utilization efficiencies (Tables 2-5, 2-11, and 2-12). In the lactating sow model, two efficiencies are considered, reflecting utilization of either dietary SID amino acid intake or amino acids from body protein mobilization for output of amino acids with milk.

The approach to representing amino acid requirements to cover endogenous GIT amino acid losses and integument amino acid losses of lactating sows is identical to that described for gestating sows, except that the GIT lysine losses per kilogram of feed intake were assumed to be 0.2827 g (Chapter 2, Proteins and Amino Acids). Negative maternal body energy balance-induced body protein mobilization is assumed to contribute essential amino acids and N for output in milk. Total SID lysine requirements represent the sum of SID lysine requirements to cover endogenous GIT lysine losses and integument lysine losses and SID lysine requirements for milk production.

The dietary SID lysine requirements for milk production are estimated from daily milk N output and maternal body protein mobilization (Eq. 8-76). The efficiency of using amino acids from mobilized body protein for amino acid output with milk (0.868) is assumed to be identical for all essential amino acids and N and similar to the energetic efficiency of utilizing body energy reserves for milk energy output. The prediction of SID lysine requirements for milk production is highly sensitive to the efficiency of using SID lysine intake over and above maintenance lysine requirements for milk lysine output. This parameter (0.67; representing an adjustment to the reference value of 0.75 to account for between-animal variability) was established as outlined in Chapter 2 (Figure 2-4). Typical SID lysine requirements are presented in Figure 8-8.

$$\text{SID lysine requirements for milk production (g/day)} = [(\text{daily milk N output} \times 6.38 \times 0.0701 - \text{maternal body protein mobilization} \times 0.0674 / 0.868) / 0.75] \times 1.1197 \quad \text{(Eq. 8-76)}$$

The above calculations were applied to all other essential amino acids and total N, based on their ratio to lysine for each of the contributors to amino acid requirements (Chapter 2, Tables 2-5 and 2-11). The absolute rates of minimum plus inevitable catabolism (e.g., the value 0.75 in Eq. 8-76; Table 2-12) were adjusted for threonine and tryptophan to match model-generated estimates of SID amino acid requirements with empirical estimates of amino acid requirements (Chapter 2, Proteins and Amino Acids). For the other amino acids, rates of minimum plus inevitable catabolism were forced to match model-generated estimates of requirements with requirements presented in NRC (1998) for lactating sows (sow initial BW 175 kg; 10 piglets gaining 250 g/day; sow BW loss 10 kg during 21-day lactation). For methionine and methionine plus cysteine, the rate of minimum plus inevitable catabolism was deemed too high (0.778 and 0.823, respectively), relative to the estimate of minimum plus inevitable catabolism obtained for the growing-finishing pig model, and additional adjustments were made (Table 2-12). A value of 0.85 was used for N, which is identical to the value used in the growing-finishing pig model.

Calcium and Phosphorus Requirements

The general approach used to estimate requirements for STTD P is similar to that for growing-finishing pigs and gestating sows (Chapter 6, Minerals), and reflect (1) P output with milk, (2) basal endogenous gut P losses (190 mg/kg feed dry matter intake), (3) minimum urinary P losses (7 mg per kg BW), (4) marginal efficiency of using STTD P intake for P output with milk (0.77), and (5) the contribution of body protein losses–induced body P mobilization. Phosphorus

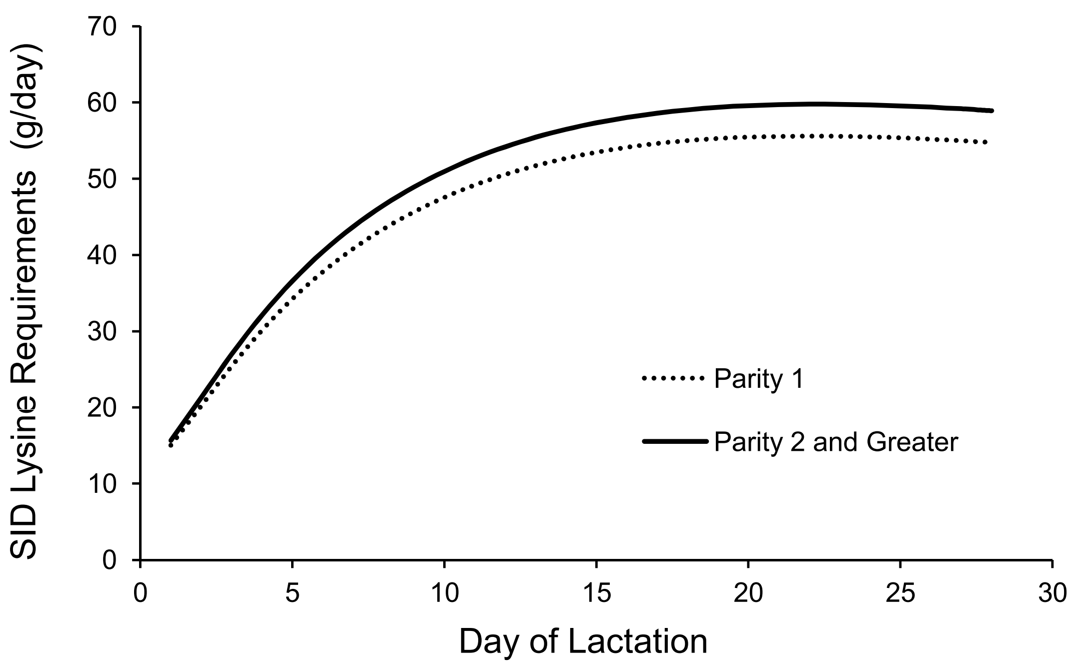

FIGURE 8-8 Simulated SID lysine requirements (g/day) of lactating sows during parity 1 and parity 2 and greater. The parity-1 sow is assumed to weigh 175 kg at the start of lactation and to nurse 11 piglets with a mean piglet weight gain of 230 g/day over a 28-day lactation period. The parity-2 and up sows are assumed to weigh 210 kg at the start of lactation and to nurse 11.5 piglets with a mean piglet weight gain of 230 g/day over a 28-day lactation period.

output in milk is calculated from milk N output, based on a fixed ratio of 0.1955 (Chapter 6, Minerals) (Jondreville and Dourmad, 2005, 2006). It is assumed that sows mobilize 9.6 mg P from body reserves per gram of maternal body protein loss (Jongbloed et al., 1999). A fixed ratio of 2.0 is used to calculate Ca requirements from STTD P requirements (Chapter 6, Minerals).

STARTING PIGS

The growth model does not generate estimates of nutrient requirements for pigs weighing less than 20 kg BW, because of insufficient information on biological relationships in these animals. Instead, a relatively simple mathematical approach was used to generate estimates of amino acid requirements.

For pigs weighing less than 20 kg BW, daily feed intake was estimated from a modification of an NRC (1987) equation (Eq. 8-77). At low dietary energy density, feed intake can be constrained by the pig's feed intake capacity (Eq. 8-15).

$$\text{ME intake (kcal/day)} = -783.5 + 315.9 \times \text{BW} - 5.7685 \times \text{BW}^2 \quad \text{(Eq. 8-77)}$$

Empirical estimates of SID lysine requirements (percent of diet) were related to a mean BW for pigs between 5 and 20 kg. The regression equation represents the best-fitting line through the following estimated requirements based on empirical data (Chapter 2, Proteins and Amino Acids; Eq. 8-78): 1.50% SID lysine at 6 kg, 1.35% SID lysine at 9 kg, and 1.23% SID lysine at 18 kg BW.

$$\text{SID lysine requirements (\% of diet)} = 1.871 - 0.22 \times \ln(\text{BW}) \quad \text{(Eq. 8-78)}$$

In order to calculate requirements for other amino acids, the daily SID lysine requirements were partitioned into requirements for body maintenance functions, using Eqs. 8-40 and 8-41, and requirements for growth, calculated as the difference between total SID lysine requirements and SID lysine requirements for body maintenance functions. Based on the balance in which amino acids and N are required for various body functions (Tables 2-5, 2-8, and 2-12), the requirements for other amino acids and N were then calculated, as outlined earlier for growing-finishing pigs. The resulting estimated optimum dietary amino acid balance appears reasonably consistent with empirically estimated amino acid requirements.

This approach to estimating amino acid requirements does not consider differences in pig growth potential or differences in health status, both of which can impact nutrient requirements of pigs below 20 kg BW. Also, gender, temperature, and space per pig are not considered.

The user has to be aware that the growth model does not always allow a smooth transition in the amino acid requirements from the end of the starting phase (19.9 kg BW) to the beginning of the growing phase (20 kg BW), simply because different approaches are used to estimate nutrient requirements for pigs below and above 20 kg BW.

Requirements for STTD P (% of diet) are related to BW in a similar manner (Eq. 8-79).

$$\text{STTD P requirements (\% of diet)} = 0.6418 - 0.1083 \times \ln(\text{BW}) \quad \text{(Eq. 8-79)}$$

The ratio between total Ca and STTD P requirements is varied with BW as well.

$$\text{Total Ca / STTD P requirements} = 1.548 + 0.9176 \times \ln(\text{BW}) \quad \text{(Eq. 8-80)}$$

MINERAL AND VITAMIN REQUIREMENTS

Traditional modeling procedures were not used to estimate the requirements for minerals and vitamins, other than P and Ca. Instead, estimates were made from empirical experiments. Estimates were made on a dietary concentration basis for six weight ranges of pigs (5-7, 7-11, 11-25, 25-50, 50-75, 75-100, and 100-135 kg BW) and for gestating and lactating sows. Exponential equations were then used to fit the midpoints of these weight ranges for either starting pigs (5 to 25 kg BW) or growing-finishing pigs (25 to 135 kg BW), by means of the following equation:

$$\text{Requirement} = a + b \times \ln(\text{BW}) \quad \text{(Eq. 8-81)}$$

Actual values for these parameters are presented in Table 8-2. An example of how the equation gives the requirement for a vitamin (riboflavin) compared with the estimated requirements for the various weight categories of pigs from 3 to 120 kg BW is shown in Figure 8-9. Note that the equation gives a requirement value that intersects the estimated requirement at approximately the midpoint of the body weight range. The individual coefficients for the prediction equations for the minerals and vitamins are shown in Table 8-2. The daily requirements were calculated by multiplying the predicted dietary concentrations by typical daily feed intakes and based on typical diet energy densities (Eq. 8-9; Table 16-1). If feed intakes deviate from typical feed intakes, then dietary requirements that are expressed on a dietary concentration basis are adjusted to meet the daily requirements.

Exponential equations were not used to estimate mineral and vitamin requirements for gestating or lactating sows. Daily requirements of minerals and vitamins for sows were calculated by multiplying the estimated dietary concentrations by the daily feed intake.

TABLE 8-2 Coefficients Used in the Growth Model to Predict Daily Mineral, Vitamin, and Linoleic Acid Requirements for Pigs of Various Body Weights[a]

	Starting Pigs			Growing-Finishing Pigs		
	Coefficients			Coefficients		
Nutrient	a	b	R^2	a	b	R^2
Minerals						
Sodium (g/day)	–1.3128	1.3339	0.9994	–2.5588	1.1335	0.9979
Chlorine (g/day)	–1.0885	1.3955	0.9789	2.0706	0.9068	0.9979
Magnesium (g/day)	–0.32	0.2349	0.9966	1.0353	0.4534	0.9979
Potassium (g/day)	–1.7815	1.4257	0.9981	0.4591	1.0774	0.9827
Copper (mg/day)	–3.0925	2.6471	0.9974	0.8705	1.9286	0.9423
Iodine (mg/day)	–0.112	0.0822	0.9966	0.3624	0.1587	0.9979
Iron (mg/day)	–79.992	58.718	0.9966	34.357	15.904	0.7342
Manganese (mg/day)	–1.4927	1.4727	0.9810	5.1766	2.2669	0.9979
Selenium (mg/day)	–0.1546	0.1324	0.9974	0.0924	0.1048	0.9043
Zinc (mg/day)	–45.852	41.198	0.9932	70.251	43.634	0.9810
Vitamins						
Vitamin A (IU/day)	–991.67	897.61	0.9924	3,364.8	1,473.5	0.9979
Vitamin D_3 (IU/day)	–141.84	111.66	1.000	388.24	170.02	0.9979
Vitamin E (IU/day)	–4.2638	5.015	0.9489	28.471	12.468	0.9979
Vitamin K (menadione) (mg/day)	–0.4	0.2936	0.9966	1.2941	0.5667	0.9979
Biotin (mg/day)	–0.0225	0.0229	0.9166	0.1294	0.0567	0.9979
Choline (g/day)	–0.1709	0.1844	1.0000	–0.7765	0.34	0.9979
Folacin (mg/day)	–0.24	0.1762	0.9966	0.7765	0.34	0.9979
Niacin, available (mg/day)	–23.997	17.616	0.9966	77.649	34.004	0.9979
Pantothenic acid (mg/day)	–5.124	4.5637	0.9943	12.202	6.6304	0.9933
Riboflavin (mg/day)	–1.5868	1.4702	0.9945	2.2184	1.615	0.9618
Thiamin (mg/day)	–0.5079	0.4792	0.9403	2.5883	1.1335	0.9979
Vitamin B_6 (mg/day)	1.2285	0.6063	0.2230	2.5883	1.1335	0.9979
Vitamin B_{12} (μg/day)	–8.2708	7.5456	0.9994	16.64	–0.852	0.0474
Linoleic acid (g/day)	–0.7999	0.5872	0.9966	–2.5883	1.1335	0.9979

[a]Estimated requirements = a + b × ln(BW), where BW is body weight in kilograms. Body weights used in the derivation of the equations represented the midpoints of the weight ranges of 5-7, 7-11, 11-25 for starting pigs, and 25-50, 50-75, 75-100, and 100-135 kg for growing-finishing pigs. These equations will give values that approximate the mineral and vitamin requirements for pigs of these weight ranges shown in Table 16-5B.

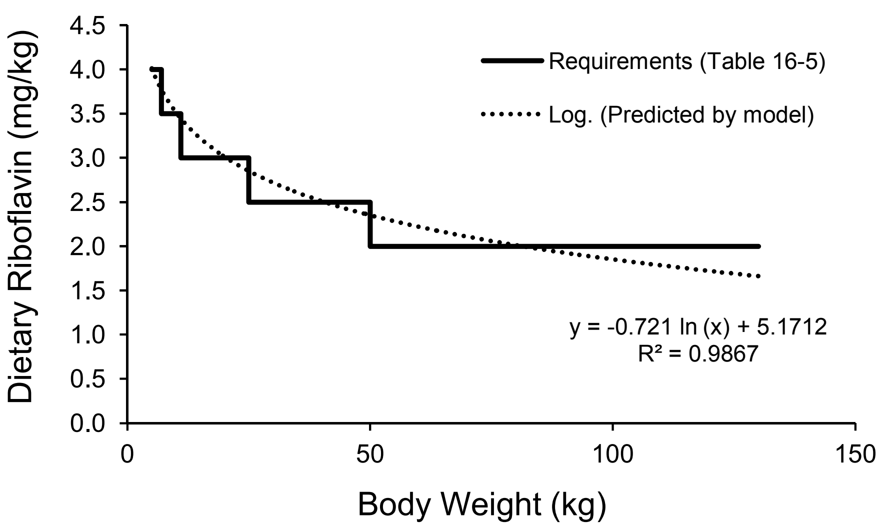

FIGURE 8-9 Estimated dietary riboflavin requirements (mg/kg of diet) for 5-135 kg body weight using the generalized exponential equation in the model.

ESTIMATION OF NITROGEN, PHOSPHORUS, AND CARBON RETENTION EFFICIENCIES

In the three models, a mass balance approach can be used to calculate the efficiency of retaining dietary N, P, and carbon intake in body weight gain of growing-finishing pigs, gestating sows, and lactating sows plus nursing piglets, respectively. The inefficiency of retention represents excretion of these elements with feces, urine, and—in the case of carbon—expired breath. Excretion of these elements can contribute to environmental degradation and may be considered in nutrient management planning.

For calculating N, P, and carbon balances, feed usage (feed intake plus feed wastage), diet ingredient compositions, and (phase-) feeding programs have to be specified by the user. In the feeding program, information has to be provided on the various diets that are fed at different stages of production. Dietary levels of N (crude protein × 0.16), P, and carbon are calculated from diet ingredient compositions, whereby carbon content in ingredients is calculated from nutrient composition (Eq. 8-82) and assuming that crude protein, crude fat, starch, sugars, and the remaining organic material contain 53, 76, 44, 42, and 45% carbon, respectively (Kleiber, 1961). Cumulative intake of N, P, and carbon is calculated from daily feed intakes, including wasted feed, and diet nutrient contents.

$$\begin{aligned}&\text{Carbon content (g/kg)} = \\ &\text{Crude protein content (g/kg)} \\ &\times 0.53 + \text{crude fat content (g/kg)} \times 0.76 \\ &+ \text{starch content (g/kg)} \times 0.44 \\ &+ \text{sugar content (g/kg)} \times 0.42 \\ &+ \text{remaining organic material content (g/kg)} \\ &\times 0.45 \qquad \text{(Eq. 8-82)}\end{aligned}$$

Retention of N (crude protein × 0.16), P, and carbon (Pd × 0.53 + Ld × 0.76) is calculated on a daily basis and summed over the entire production period for deriving nutrient retention efficiencies. Daily values for Pd and Ld are calculated according to energy-partitioning calculation rules that are represented in Eqs. 8-31 (growing-finishing pigs), 8-65 (gestating sows), and as described earlier in this chapter, in the section "Partitioning of ME Intake" for lactating sows. In the case of gestating sows, protein and lipid gain in products of conceptus are calculated as well, with lipid gain calculated from the difference between total energy gain and protein energy gain (Eqs. 8-55 to 8-57). Daily P retention is calculated using Eq. 8-47 (growing-finishing pigs), Eq. 8-67, and Eq. 8-68 (gestating sows and also considering P retention in the maternal body) and as outlined in the section "Calcium and Phosphorus Requirements" for lactating sows. In the case of growing-finishing pigs, it is assumed that P retention is maximized (Eq. 8-47). Based on a review of the literature, it is assumed that nursing piglets retain 15.3 g protein, 16.5 g lipid, and 0.00393 g P per 100 g of body weight gain (Zijlstra et al., 1996; Mathews, 2004; Ebert et al., 2005; Birkenfeld et al., 2006; Canario et al., 2007; Bergsma et al., 2009; Losel et al., 2009; Pastorelli et al., 2009; Charneca et al., 2010).

Nitrogen, P, and carbon balances are calculated for the entire production period. For growing-finishing pigs, nutrient balances can also be calculated for part of the growing-finishing period. In these calculations, it is assumed that intake of dietary nutrients does not limit animal performance and, thus, that the levels of essential nutrients in each of the diets always exceed the animal's nutrient requirements. Feeding diets that do not meet the animal's nutrient requirements invalidates the N, P, and carbon balance calculations.

EVALUATION OF THE MODELS

The models were evaluated in four ways:

(1) subjective evaluation of the response of model predictions to changes in input values by experts (behavioral analysis);

(2) tests of the sensitivity of model predictions to changes in selected model parameters;

(3) direct comparison of estimated amino acid and P requirements to the models presented in NRC (1998); and

(4) simulation of experimental data reported in the literature, and comparison of simulated values to measured responses and requirements.

The main modeling concepts and many of the model parameters, in particular those related to partitioning of energy intake and chemical body composition, have been derived from existing models and have therefore been evaluated previously (Agricultural Research Council, 1981; NRC, 1998; de Lange et al., 2003; Jongbloed et al., 2003; Schinckel et al., 2006; Dourmad et al., 2008; GfE, 2008; van Milgen et al., 2008; Bergsma et al., 2009). The models were peer-reviewed and the general behavior was found to be reasonable (changes in energy intake and in user-defined levels of pig performance resulted in reasonable changes in simulated body weight changes and nutrient requirements). For example, the impact of feeding RAC or immunization against GnRH on growth performance and estimated lysine requirements is consistent with the opinion of experts and, in the case of feeding RAC, consistent with results of empirical animal performance and lysine requirement studies (e.g., Apple et al., 2004, 2007; Webster et al., 2007).

Based on sensitivity analyses, critical model parameters were identified, such as SID lysine requirements per 100 g Pd, the relationship between litter growth rate and milk N output, endogenous GIT lysine losses, amino acid profiles (of Pd, milk protein, and protein gain in fetus and other tissues involved in reproduction), the postabsorptive efficiency of amino acid utilization, and relationships between P and N retention in milk and in the pig's body. Estimates of these critical parameters were obtained based on an extensive review of the literature, as described in previous sections and in Chapters 1 (Energy), 2 (Proteins and Amino Acids), and 6 (Minerals).

In the following sections, results of model simulations are compared to levels of animal performance and nutrient requirements as presented in NRC (1998) or observed in individual studies. These comparisons are consistent with the intended use of the models and can be considered evaluations at a high level of aggregation; they reflect cumulative effects of energy utilization, relationships between chemical and physical body composition, and nutrient utilization for biological processes that contribute to amino acid and P requirements.

In some instances, experimental observations were used for generating estimates of model parameters and for comparison to simulated nutrient requirements. This applies in particular when only very few well-controlled studies have been published to determine requirements for a particular nutrient. Therefore, this cannot be considered a valid testing of the model with data that were not used in model development. However, such analyses provide confidence that the model is consistent with experimental observations and its intended use.

Growing-Finishing Pig Model

In Figure 8-10A, B, C, D, and E, model-estimated SID requirements are related to observed SID requirements for lysine, threonine, methionine, methionine plus cysteine, and tryptophan in carefully selected requirement studies and as outlined in Chapter 2 (Proteins and Amino Acids). For each of these amino acids, the relationships are highly linear, with slopes and intercepts that are not different from 1 and 0, respectively, suggesting accurate prediction of absolute requirements. For the other essential amino acids, the number of studies was insufficient to conduct such analyses. Figure 8-11 illustrates that the model-predicted SID lysine requirements per kg body weight are similar to observed requirements. This provides confidence that changes in both SID lysine requirements and body composition with increases in BW are represented reasonably well in the new model.

In Table 8-3, model-generated estimates of requirements for SID amino acids, STTD P, and total Ca are compared directly to NRC (1998) for the levels of performance that were specified in Table 10-1 of NRC (1998). To allow evaluation of STTD P requirements, corn and soybean meal diets were formulated based on nutrient specifications for ingredients and available P requirements according to NRC (1998). The resulting dietary feed ingredient compositions were then used to calculate STTD P requirements based on STTD P contents in these ingredients, according to values included in this publication. Based on this comparison, the new model yields estimates of lysine requirements that are about 3% lower in pigs between 20 and 50 kg BW, and about 8% higher in pigs between 100 and 130 kg BW. These differences are consistent with increased estimates of maintenance lysine requirements and increases in lysine requirements per 100 g Pd with increasing BW in the new model (Chapter 2, Proteins and Amino Acids). In NRC (1998), lysine requirements per 100 g Pd were assumed to be independent of BW. By implementing these adjustments, the apparent underestimation of estimated lysine requirements of pigs between 80 and 120 kg body weight that was noted in NRC (1998) has been addressed.

Relative to lysine, requirements for methionine and arginine are increased and requirements for isoleucine and tryptophan are reduced in the new model. These changes in requirements are consistent with recent studies (Chapter 2, Proteins and Amino Acids). Despite the lack of meaningful and recent histidine requirement estimates, histidine requirements are increased in the new model. Lowering the model-generated estimates of histidine requirements would require an apparent postabsorptive efficiency of histidine utilization of more than 100%, which is deemed unrealistic. For other amino acids, the new model yields minor changes in requirements, when expressed relative to those of lysine.

The requirements for STTD P have been reduced in the new model, largely based on European reviews on P requirements (Jongbloed et al., 1999; BSAS, 2003; Jondreville and Dourmad, 2005, 2006; GfE, 2008). Unlike the NRC (1998) model, dietary P requirements vary with pig growth rate, driven by changes in Pd. As a result, dietary P requirements are estimated to be higher in entire males than in gilts and barrows, which is consistent with empirical observations (Chapter 6, Minerals). In pigs with high rates of Pd, the dietary P requirement estimates approach values suggested by NRC (1998) and exceed requirements according to Jongbloed et al. (1999), Jondreville and Dourmad (2005, 2006), BSAS (2003), and GfE (2008). These principles also apply to Ca requirements, which are estimated directly from those of STTD P. Relative to P, Ca requirements are slightly increased from NRC (1998).

To simulate performance data of individual nutrient requirement studies, observed feed and energy intake levels were entered in the model, as well as the BW range for which nutrient requirements were determined. It was assumed that feed wastage represented 5% of documented feed intake plus wastage. The mean Pd was varied to match observed and simulated BW gains and feed efficiencies. The default shape of the gender-specific Pd curves was not altered. When information on probe backfat thickness was available, this information was entered as well and the adjustment to maintenance energy requirements was varied to match observed with simulated backfat thickness. After the model was calibrated (e.g., observed and predicted growth rate and backfat thickness were matched by varying mean lean tissue growth rates and maintenance energy requirements), nutrient requirements were simulated and compared to determined requirements. As an example, estimated lysine requirements

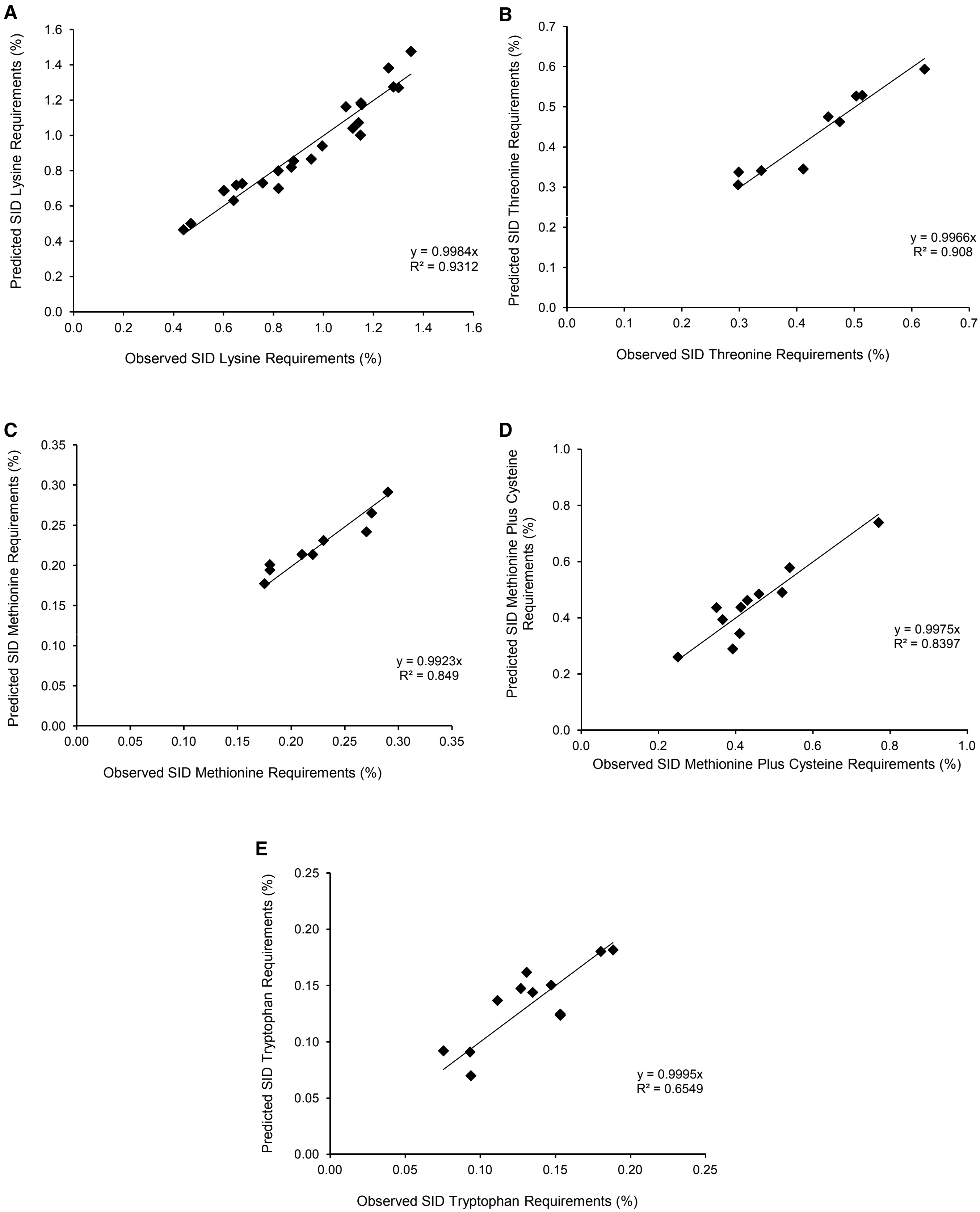

FIGURE 8-10 Relationship between model-predicted and observed SID (A) lysine, (B) threonine, (C) methionine, (D) methionine plus cysteine, and (E) tryptophan requirements (% of diet) of growing-finishing pigs. Data are presented in Table 2-2 and Figures 2-3A to 2-3E.

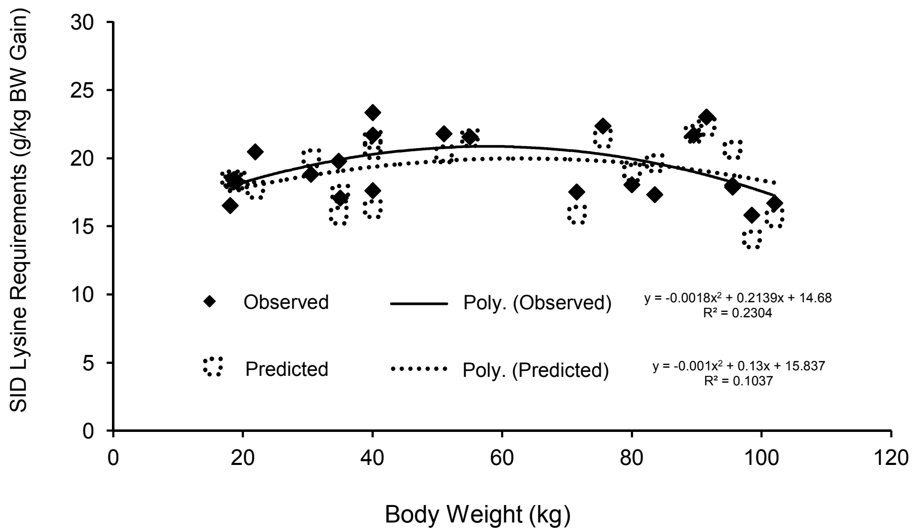

FIGURE 8-11 Relationships between observed or model-predicted SID lysine requirements (g/kg BW gain) and mean BW. Data are presented in Table 2-2 and Figure 2-3A.

TABLE 8-3 Estimated Requirements for Standardized Ileal Digestible (SID) Amino Acids, Total Calcium, and Standardized Total Tract Digestible (STTD) Phosphorus According to the New Growing-Finishing Pig Model and NRC (1998) for Levels of Performance Specified in NRC (1998, Table 10-1)[a]

Body Weight (kg)	20-50		50-80		80-120	
Diet ME content (kcal/kg)	3,265		3,265		3,265	
Estimated ME intake (kcal/day)	6,050		8,410		10,030	
Source	NRC 1998	New	NRC 1998	New	NRC 1998	New
Estimated feed intake (g/day)	1,855	1,821	2,575	2,579	3,075	3,097
SID lysine (% of diet)	0.83	0.80	0.66	0.67	0.52	0.56
SID lysine (g/day)	15.3	14.6	17.1	17.4	15.8	17.2
SID amino acids (requirements relative to lysine)						
Arginine	39.8	45.9	36.4	46.0	30.8	46.1
Histidine	31.3	34.4	31.8	34.4	30.8	34.4
Isoleucine	54.2	50.8	56.1	51.3	55.8	52.0
Leucine	100.0	101.1	101.5	101.5	98.1	102.0
Lysine	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**
Methionine	26.5	28.9	27.3	28.8	26.9	28.8
Methionine + cysteine	56.6	57.0	59.1	57.8	59.6	58.9
Phenylalanine	59.0	60.2	60.6	60.7	59.6	61.3
Phenylalanine + tyrosine	94.0	94.7	95.5	95.5	94.2	96.6
Threonine	62.7	62.5	65.2	64.5	65.4	67.2
Tryptophan	18.1	17.4	18.2	17.7	19.2	18.2
Valine	67.5	65.8	68.2	66.6	67.3	67.7
N × 6.25	—	1,367.5	—	1,391	—	1,424
Calcium, total (% of diet)	0.60	0.52	0.50	0.45	0.45	0.39
Phosphorus, available (% of diet)	0.23	—	0.19	—	0.15	—
Phosphorus, STTD (% of diet)	0.30	0.24	0.26	0.21	0.21	0.18

[a]Feed wastage is not considered and assumed to be 0%.

are compared to experimentally determined requirements observed in studies by Coma et al. (1995) and Dourmad et al. (1996) (Table 8-4). These studies were not used for model development as outlined in Chapter 2 and comparisons can be considered an independent test of the model. The results that are summarized in Table 8-4 suggest reasonable agreement between observed and model-generated estimates of dietary lysine requirements. The model appears to systematically overestimate lysine requirements of pigs that are housed individually, which can be attributed to the reduced postabsorptive efficiency of lysine utilization in the model to reflect the impact of between-animal variability on nutrient requirements (e.g., Pomar et al., 2003). These results also show that the new model provides a reasonable representation of the interactive effects of feeding level and BW (Coma et al., 1995), as well as of gender and BW (Dourmad et al., 1996) on lysine requirements. Based on these results and other analyses (e.g., Figure 8-10A), no meaningful and systematic biases were identified for predicting lysine requirements of growing-finishing pigs housed in groups.

There are potential biases when model-generated estimates of requirements for lysine and other nutrients are obtained, especially those for wide BW ranges or for groups of pigs with highly variable performance potentials. Empirical estimates of lysine requirements are established in growth performance studies that are conducted over a substantial time period and when considerable BW gain is achieved. Growing pigs are expected to respond to higher dietary lysine concentrations during the early part of the experiment, simply because dietary lysine requirements decline with increasing BW (e.g., Figure 2-3A). Therefore, the experimentally determined requirement, expressed as percentage of the diet, is applicable to pigs near the initial BW. However, feed intake and growth performance are usually reported for the entire trial period. For this reason, the model calculates the mean of daily dietary lysine requirements and will underestimate requirements of pigs near the initial BW. Along the same lines and due to between-animal variability in performance potentials, estimated nutrient requirements will be higher in groups of animals than in individually housed animals (e.g., Pomar et al., 2003). To some extent, these potential biases have been captured in the interpretation of lysine requirements and in the adjustment of lysine utilization efficiency, as outlined earlier in this chapter and in Chapter 2 (Proteins and Amino Acids). However, these biases remain when estimating requirements for lysine and other nutrients over wide BW ranges or for groups of pigs with highly variable performance potentials. In order to minimize these sources of bias, nutrient requirement studies that cover more than 20 kg of growth in growing pigs and more than 30 kg in finishing pigs, or reporting highly variable pig performances, have to be interpreted with caution and thus were not considered in this evaluation. These potential biases have to be considered when using models to estimate nutrient requirements.

TABLE 8-4 Experimentally Determined Versus Model-Predicted Lysine Requirements of Growing-Finishing Pigs

Gender	BW Range (kg)	Feed Intake + Wastage (g/day)	Observed BW Gain (g/day)	Estimated Mean Lean Gain (g/day)	Lysine Requirement (% of diet): Determined	Predicted	Difference[a] (%)
						Total lysine	
Coma et al. (1995)[b]							
Barrow	27.1-35.4	1.864	—	325	0.97	0.95	–2
Barrow	27.1-35.4	1.282	—	325	1.01	1.05	4
Barrow	92.6-104	3.543	—	325	0.61	0.61	0
Barrow	92.6-104	2.643	—	325	0.85	0.76	–10[b]
						SID lysine	
Dourmad et al. (1996)[c]							
Barrow	50-80	2.251	779	329	0.68	0.78	15
Gilt	50-80	2.244	850	377	0.71	0.81	14
Barrow	80-110	2.822	896	329	0.56	0.65	17
Gilt	80-110	2.841	950	377	0.68	0.71	4

[a]100 × (predicted requirement – determined requirement) / (determined requirement).

[b]Pigs were fed restricted corn and soybean meal–based diets with graded levels of added lysine; the estimated diet ME content was 3,261 and 3,271 kcal/kg for the lower and higher BW ranges, respectively; 5% feed wastage was assumed; mean per treatment growth performance data were not presented in the manuscript; a constant mean lean gain that was previously determined for this group of pigs was used in all simulations. The determined daily lysine requirement of pigs at the higher BW was increased when feed intake was reduced (22.5 vs. 21.6 g/day; low and high intake, respectively); this anomaly explains in part the discrepancy between determined and predicted lysine requirements.

[c]Individually housed pigs were scale–fed wheat-based basal dies with graded levels of added L-lysine·HCl; the estimated diet NE content was 2,342 kcal/kg; 5% feed wastage was assumed; mean lean gain values were held constant across the two BW ranges for the two genders and estimated using the model and based on matching observed with predicted BW gains. The systematic overestimation of lysine requirements is likely to reflect that observations were made on individual pigs rather than groups of pigs.

Gestating Sow Model

As indicated in NRC (1998), Chapter 2 (Proteins and Amino Acids), and Chapter 6 (Minerals), very few well-controlled nutrient requirement studies have been conducted with gestating sows. Therefore, extreme care was taken to quantify the main determinants of amino acid, P, and Ca requirements and to refine the gestating sow model that was described in detail by Dourmad et al. (2008). Major refinements of the Dourmad et al. (2008) model are the representation of amino acid profiles in the various protein pools for estimation of amino acid requirements, the inclusion of piglet birth weight—in addition to litter size—to characterize growth of products of conceptus, the representation of the impact of parity on the relationship between energy intake and maternal body protein deposition, and the representation of P retention in products of conceptus and the maternal body.

The results presented in Table 8-5 demonstrate that the new gestating sow model slightly underpredicts sow BW and backfat changes during gestation and across parities. In the gestating sow model, predicted performance is highly sensitive to estimated maintenance energy requirements. For example, for the parity-4 sow results that are presented in Table 8-5, and where the discrepancy between predicted and observed performance is largest, reducing maintenance energy requirements by only 13%, from the default value of 100 kcal per kg $BW^{0.75}$, will increase estimated sow BW change to 39.7 kg and backfat change to 2.7 mm and approach observed values. However, maintenance energy requirements of gestating sows that are managed under commercial conditions are variable and likely higher than 87 kcal per kg $BW^{0.75}$. Therefore, the default value for maintenance energy requirements is maintained in the model. Model users may judiciously use the adjustment to maintenance energy requirements to match observed with predicted sow BW and backfat changes during gestation. Based on these and other analyses, it is concluded that the model provides a reasonable representation of the response to energy intake and the partitioning of retained energy between protein and lipid gain in the sow's body and products of conceptus.

The gestating sow model was forced to be consistent with three carefully selected lysine requirement studies, by manipulating the efficiency of using SID lysine intake for lysine retention in Pd and as outlined earlier in this chapter, and yielding estimates of lysine requirements that are slightly higher than those generated using the Dourmad et al. (2008) gestating sow model.

In Table 8-6, model-generated estimates of requirements for SID amino acids, STTD P, and total Ca are compared directly to NRC (1998) for the levels of performance that were specified in Table 10-8 of NRC (1998). Based on this comparison, the new model yields estimates of mean lysine requirements over the 114-day gestation period that are slightly higher in parity-1 sows, slightly lower in parity-2 sows, and substantially lower in parity-3 and -4 sows. These differences can be attributed largely to changes in maternal body protein deposition across parities, which are larger in the new model than in NRC (1998). Relative to lysine, requirements for tryptophan and valine are increased and

TABLE 8-5 Observed Versus Model-Predicted Gestation Weight and Backfat Changes During Gestation[a]

Parity	1[b]	2[c]	3[d]	4[e]
Observed performance				
Body weight at breeding (kg)	135.4	158.3	196.4	184.8
Gestation weight gain (kg)	67.4	56.3	46.4	42.4
Backfat at breeding (mm)	16.3	17.2	16.9	17.9
Backfat gain during gestation (mm)	4.5	2.5	2.6	1.7
Litter size	10.7	10.8	11.4	11.1
Feed intake + feed wastage (kg/day)	2.334	2.285	2.327	1.983
Diet ME content (kcal/kg)	3,100	3,145	3,240	3,257
Model-predicted performance				
Gestation weight gain (kg)	61.8	51.8	44.9	33.1
Backfat gain during gestation (mm)	2.3	2.2	1.7	–0.6

[a]Observed mean values per parity were simulated. Mean piglet birth weight was assumed to be 1.4 kg across all parities. It was assumed that feed wastage was 5%. In the model, default values were used for the two model calibration parameters (maintenance energy requirements; relationship between maternal body N gain and energy intake). The degree of fit between observed and predicted body weight and backfat at farrowing can be improved by adjusting these two model calibration parameters. For example, in parity-4 sows a reduction in maintenance energy requirements by 13% increases gestation weight gain to 39.7 kg and backfat gain during gestation to 2.7 mm.

[b]For parity-1 sows, observed performance represents the mean of values observed by Mahan (1998), Cooper et al. (2001), van der Peet-Schwering et al. (2003), Gill (2006), and Dourmad et al. (2008) (n = 5).

[c]For parity-2 sows, observed performance represents the mean of values observed by Mahan (1998), Cooper et al. (2001), van der Peet-Schwering et al. (2003), and Veum et al. (2009) (n = 4).

[d]For parity-3 sows, observed performance represents the mean of values observed by Mahan (1998), Young et al. (2004; 3 means), van der Peet-Schwering et al. (2003), and Veum et al. (2009) (n = 6).

[e]For parity-4 sows, observed performance represents the mean of values observed by Mahan (1998), Musser et al. (2004), and Veum et al. (2009) (n = 3).

TABLE 8-6 Estimated Requirements for Standardized Ileal Digestible (SID) Amino Acids, Total Calcium, and Standardized Total Tract Digestible (STTD) Phosphorus According to the New Gestating Sow Model and NRC (1998) for Levels of Performance Specified in NRC (1998, Table 10-8)[a]

Body Weight at Breeding (kg)	125		150		175		200	
Parity	1		2		3		4	
Gestation weight gain (kg)	55		45		40		35	
Litter size	11		12		12		12	
Diet ME content (kcal/kg)	3,265		3,265		3,265		3,265	
Source	NRC, 1998	New	NRC, 1998	New	NRC, 1998	New	NRC, 1998	New
Estimated feed intake (kg/day)	1.96	1.892	1.84	1.847	1.88	1.927	1.92	1.987
SID lysine (% of diet)	0.50	0.56	0.49	0.47	0.46	0.40	0.44	0.35
SID lysine (g/day)	9.7	10.6	9.0	8.6	8.7	7.7	8.4	6.9
SID amino acids (requirements relative to lysine)								
Arginine	8.2	52.5	1.1	52.1	0.0	51.8	0.0	51.4
Histidine	32.0	33.8	32.2	33.1	32.2	32.6	32.1	32.2
Isoleucine	57.7	55.6	57.8	55.8	58.6	56.3	59.5	56.8
Leucine	96.9	91.4	96.7	93.2	95.4	94.5	94.0	95.8
Lysine	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**
Methionine	27.8	28.0	27.8	27.8	27.6	27.7	27.4	27.5
Methionine + cysteine	66.0	64.6	67.8	67.2	70.1	69.3	71.4	71.6
Phenylalanine	58.8	54.8	57.8	56.1	57.5	57.1	57.1	58.1
Phenylalanine + tyrosine	97.9	95.6	98.9	97.1	98.9	98.6	100.0	100.1
Threonine	75.3	71.1	77.8	74.9	79.3	78.6	82.1	82.3
Tryptophan	19.6	18.1	20.0	19.3	19.5	20.1	20.2	21.0
Valine	68.0	70.9	67.8	73.0	67.8	74.8	67.9	76.7
N × 6.25	—	1,589.3	—	1,655.2			—	1,770.3
Calcium, total (% of diet)	0.75	0.69	0.75	0.65	0.75	0.57	0.75	0.50
Phosphorus, available (% of diet)	0.35		0.35		0.35		0.35	
Phosphorus, STTD (% of diet)	0.40	0.30	0.40	0.28	0.40	0.25	0.40	0.22

[a]Feed wastage is not considered and assumed to be 0%.

requirements for isoleucine are reduced in the new model. These changes in requirements are consistent with the amino acid composition of the various protein pools in gestating sows, and in particular that of fetal protein (Chapter 2, Proteins and Amino Acids). It is likely that the suggested changes in requirements for these three amino acids are an underestimation of the real changes that are needed. However, it was deemed that empirical estimates of requirements need to be obtained before making additional adjustments for these three and other amino acids. The requirements for STTD P and Ca have been reduced in the new model, largely based on European reviews on P requirements (Jongbloed et al., 1999; BSAS, 2003; Jondreville and Dourmad, 2005, 2006; GfE, 2008). In general, the new model yields estimated requirements for STTD P that are slightly higher than the European estimates, which is consistent with relatively low marginal efficiency of using STTD P intake for P retention. Relative to P, Ca requirements are slightly increased from NRC (1998).

A major change from NRC (1998) is that the new gestating sow model allows generation of nutrient requirements for different periods during gestation (Tables 16-6A and 16-6B). The substantial increase in daily energy, amino acid, P, and Ca requirements during late gestation is consistent with development patterns for various tissues during gestation (Chapter 2, Proteins and Amino Acids), European recommendations (Dourmad et al., 2008; GfE, 2008), observed changes in N retention during gestation in modern sows (Srichana, 2006), and recent estimates of lysine requirements obtained with the indicator amino acid oxidation technique (Moehn et al., 2011). Largely because of the rapid changes in nutrient requirements during late gestation, mean estimated nutrient requirements are highly sensitive to the time periods that are chosen. If only one diet can be fed throughout the gestation period, it is suggested to formulate this diet to meet nutrient requirements during days 90 to 114 of gestation; across parities these requirements are higher than the requirements according to NRC (1998) (Tables 16-6A and 16-6B).

Lactating Sow Model

In Figure 8-12, the relationship between model-estimated SID lysine requirements of lactating sows and observed requirements from carefully selected studies as outlined in Chapter 2 (Proteins and Amino Acids) is presented. This relationship is highly linear, with a slope and intercept not differing from 1 and 0, respectively, suggesting accurate prediction of absolute lysine requirements. For the other es-

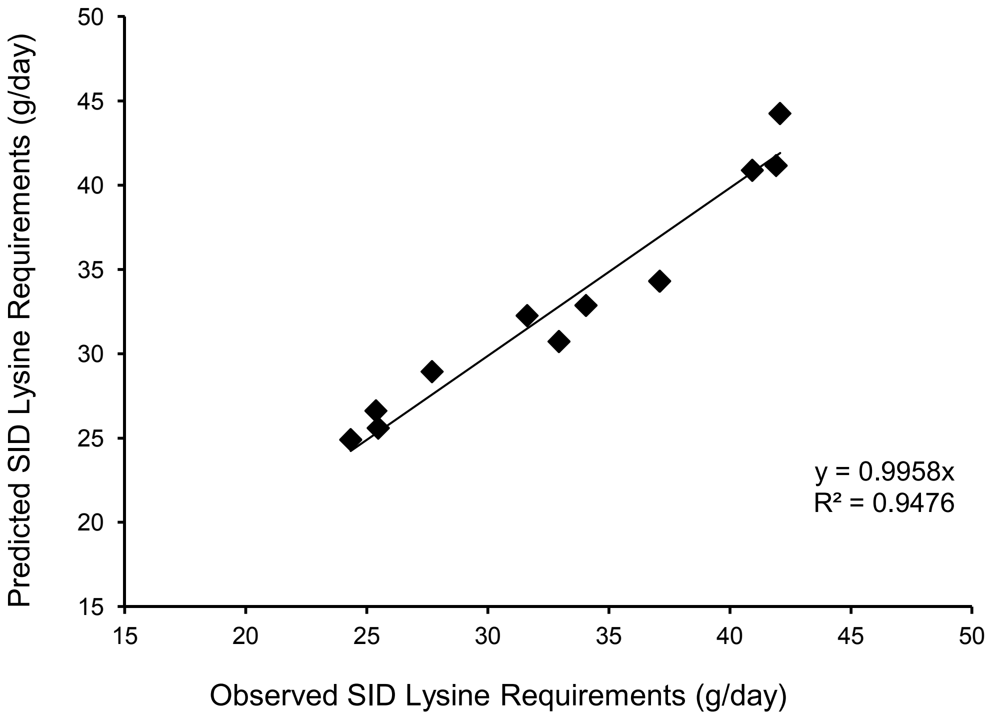

FIGURE 8-12 Relationship between model-predicted and observed SID lysine requirements (g/day) of lactating sows. Data are presented in Table 2-3 and Figure 2-5.

sential amino acids, the number of studies was insufficient to conduct such analyses.

In Table 8-7, model-generated estimates of requirements for SID amino acids, STTD P, and total Ca are compared directly to NRC (1998) for the levels of performance that were specified in Table 10-10 of NRC (1998). These results illustrate that the performance response to energy intake is very similar for NRC (1998) and the new lactating sow model. However, the new model yields estimates of mean lysine requirements over a 21-day lactation period that are 11-15% lower than requirements according to NRC (1998). This discrepancy increases with increasing sow BW loss during lactation. The latter can be attributed to the more mechanistic representation of the contribution of negative energy balance–induced sow body protein losses to milk lysine output in the new model (Chapter 2, Proteins and Amino acids). Differences between the new model and NRC (1998) can in part be attributed to the correction of daily nutrient intake for 5% assumed feed wastage in nutrient requirement studies, which directly impacts estimates of daily lysine requirements. Feed wastage was not considered in NRC (1998). When using the new model, it is suggested that 5% feed wastage be used as the default value, which will increase lysine requirements that are expressed as dietary concentrations and presented in Table 8-7 by 5%.

The updated interpretation of lysine requirement studies that were considered in NRC (1998) also contributes to the reduction in estimated lysine requirements of lactating sows. For example, in the study by Boomgaardt et al. (1972), no response to added lysine was observed. It is thus incorrect to assume that the lowest dietary lysine level in that study reflected requirements, and, as such, this study was eliminated from the data set. In addition, a reinterpretation of the data presented by Johnston et al. (1993) yielded a substantial reduction in estimated lysine requirements. The latter study had a relatively large impact on the estimated lysine requirements per unit of litter weight gain that was used in NRC (1998). Furthermore, the new estimate of lysine requirement based on data presented by Johnston et al. (1993) yielded a substantial improvement in fit of the linear relationship between SID lysine intake and dietary lysine output with milk (Figure 2-4, Proteins and Amino Acids). Relative to lysine, requirements for threonine, tryptophan, methionine, and methionine plus cysteine are increased in the new model. For threonine and tryptophan, these changes are consistent with amino acid requirement studies (Chapter 2, Proteins and Amino Acids). For methionine and methionine plus cysteine requirements, the postabsorptive efficiencies of amino acid utilization were decreased from values required for matching NRC (1998) requirements to yield efficiencies that are more consistent with those for growing-finishing pigs and gestating sows. Milk contains substantial amounts of taurine (Wu and Knabe, 1994), which is generated from cysteine and reduces the efficiency of methionine plus cysteine utiliza-

TABLE 8-7 Estimated Requirements for Standardized Ileal Digestible (SID) Amino Acids, Total Calcium, and Standardized Total Tract Digestible (STTD) Phosphorus According to the New Lactating Sow Model and NRC (1998) for Levels of Performance Specified in NRC (1998, Table 10-10)[a]

Sow Postfarrowing Weight (kg)	175		175	
Anticipated lactational weight change (kg)	0		–10	
Daily weight gain of piglets (g)	250		250	
Diet ME content (kcal/kg)	3,265		3,265	
Source	NRC, 1998	New	NRC, 1998	New
Estimated feed intake (kg/day)	6.4	6.462	5.66	5.477
SID lysine (% of diet)	0.85	0.75	0.9	0.79
SID lysine (g/day)	54.3	48.2	51.2	43.5
SID amino acids (requirements relative to lysine)				
Arginine	57.3	57.8	54.7	54.5
Histidine	40.0	40.1	39.6	39.7
Isoleucine	55.4	55.7	55.7	55.7
Leucine	113.3	111.9	113.5	113.7
Lysine	**100.0**	**100.0**	**100.0**	**100.0**
Methionine	26.0	26.8	25.8	26.6
Methionine + cysteine	47.9	52.8	47.9	53.3
Phenylalanine	54.7	54.3	54.5	54.6
Phenylalanine + tyrosine	112.5	111.5	112.9	113.1
Threonine	61.3	64.3	61.5	64.4
Tryptophan	17.9	19.0	18.4	19.5
Valine	84.3	85.3	85.2	85.3
N × 6.25	—	1,349.6	—	1,339.8
Calcium, total (% of diet)	0.75	0.63	0.75	0.72
Phosphorus, available (% of diet)	0.35	—	0.35	—
Phosphorus, STTD (% of diet)	0.41	0.32	0.41	0.36

[a]Feed wastage is not considered and assumed to be 0%.

tion for methionine and cysteine output with milk. The new model yields estimates of optimum dietary SID methionine and methionine plus cysteine to lysine ratios that are more in line with other recommendations (e.g., BSAS, 2003; Dourmad et al., 2008; GfE, 2008). It is likely that the suggested changes in requirements for methionine and methionine plus cysteine are an underestimation of the real changes that are needed. However, it was deemed that empirical estimates of requirements need to be obtained before making additional adjustments for these and other amino acids. The requirements for STTD P and Ca have been reduced in the new model relative to NRC (1998), largely based on European reviews on P requirements (Jongbloed et al., 1999, 2003; BSAS, 2003; Jondreville and Dourmad, 2005, 2006; GfE, 2008). In general, the new model yields estimated requirements for STTD P that are slightly higher than the European estimates, which is consistent with relatively low marginal efficiency of using STTD P intake for P retention. Relative to P, Ca requirements are slightly increased from NRC (1998).

The lactating sow model was used to simulate three lysine requirement studies that were not used for model development (Table 8-8). In these three studies, sows were fed corn and soybean meal–based diets and model simulations were conducted on the basis of total dietary lysine contents. For each of these lysine requirement studies, feed intakes (corrected for 5% feed wastage), diet ME contents, sow body weight after farrowing, lactation length, number of pigs in the litter, and mean daily pig weight gains were entered in the model. When appropriate, adjustments were made to maintenance energy requirements to match observed with model-predicted sow body weight changes. Because no information was available to estimate the composition of sow BW changes, the model default value was used to estimate the relative contribution of body protein and body lipid changes to changes in body energy balance. In two of these studies (Stahly et al., 1990; Monegue et al., 1993), performance improved as the dietary lysine level increased all the way to the highest level. In those cases, the measured requirement was taken to be the highest level fed, even though the requirement for maximum performance may have been higher. This approach is appropriate in evaluation of this model because the model estimates the amount of lysine needed to reach the level of performance attained in the experiment. In both of these studies, the model yielded a slight overprediction of lysine requirements, expressed at dietary levels. In the study of Srichana (2006), lactating sows were fed five different dietary lysine levels, ranging from 0.95 to 1.35%; it was concluded that sow lactation performance was maximized at

TABLE 8-8 Experimentally Determined Versus Model-Predicted Lysine Requirements of Lactating Sows

Source	Feed Intake + 5% Wastage (kg/day)	No. of Piglets Weaned	Piglet Gain (g/day)	Total Lysine Requirements (% of diet)		
				Determined	Predicted	Difference[a]
Monegue et al. (1993)[b]	6.070	11.1	210	0.90	0.94	4%
Stahly et al. (1990)[c]	5.404	10.76	194	0.86	0.89	3%
Srichana (2006)[d]	5.400	9.1	251	0.99	1.01	2%
Srichana (2006)[e]	5.700	9.3	248	1.04	0.95	–9%

[a]100 × (predicted requirement – determined requirement) / (determined requirement).
[b]Lactation length 28 days; BW after farrowing 198 kg; BW at weaning 201.6 kg; estimated diet ME content 3,265 kcal/kg.
[c]Lactation length 27 days; BW after farrowing 186 kg; BW at weaning 181.5 kg; estimated diet ME content 3,368 kcal/kg.
[d]Treatment 1; Lactation length 19.5 days; BW after farrowing 190 kg; BW at weaning 194.1 kg; estimated diet ME content 3,460 kcal/kg.
[e]Treatment 2; Lactation length 19.2 days; BW after farrowing 190.8 kg; BW at weaning 194.8 kg; estimated diet ME content 3,460 kcal/kg.

the highest dietary lysine level, while subsequent reproductive performance was not influenced by dietary lysine level. In this study, statistically significant linear increases in both litter gain and maternal sow body weight gain with increasing dietary lysine intake were reported, even though the marginal responses to additional lysine intake were small. Based on the estimated lysine content in milk and maternal body weight gain, as outlined in Eqs. 8-71 and 8-76, the marginal utilization of SID lysine intake was estimated to be constant across dietary lysine levels and less than 15%, which is much lower than that observed in other requirement studies that are presented in Chapter 2 (Proteins and Amino acids). Based on these considerations, only the performance results for the two lowest dietary lysine levels are presented in Table 8-8. Simulations indicate that the revised model overpredicted lysine requirements to support the lactating performance of sows fed the diet containing 0.99% total lysine and underpredicted performance of sows fed the diet containing 1.04% total lysine, while sow lactation performance differed only very slightly between these two treatments. Based on these three studies, it is suggested that the lactation model provides reasonable predictions of empirically determined lysine requirements of lactating sows.

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9

Coproducts from the Corn and Soybean Industries

INTRODUCTION

Since the development of the corn–soybean meal diet in the early 1950s, most pigs in the United States have been fed diets based primarily on corn and soybean meal (Cromwell, 2000). The amino acid (AA) composition of corn and soybean meal complement each other well, with corn protein being relatively rich in the sulfur-containing AA, which are the first-limiting AA for pigs and poultry in soybean meal, and soybean meal being rich in lysine and tryptophan, which are the first-limiting AA in corn protein. Despite the popularity of the corn–soybean meal diet, pigs do not have a requirement for either of these ingredients. Instead, they require energy and specific nutrients and it is sometimes economical to provide energy and nutrients from ingredients other than corn and soybean meal. As an example, a number of corn coproducts are produced from the wet milling and dry milling industries, and there are many ingredients other than soybean meal that are produced from soybeans. Many of these ingredients are byproducts of the human food industry and they can be successfully included in diets fed to pigs.

It is the objective of this chapter to describe differences in composition and digestibility of energy and nutrients among coproducts from the corn and soybean industries that may be included in diets fed to pigs. It is beyond the scope of this publication to provide a comprehensive overview of the use of each ingredient. Numerous reviews with specific recommendations about inclusion rates and practical use of each product have been published, and several of these are cited throughout the chapter.

CORN COPRODUCTS

Distillers Dried Grains, Distillers Dried Grains with Solubles, Low-Fat Distillers Dried Grains with Solubles, and Deoiled Distillers Dried Grains with Solubles

If corn is used for the production of ethanol or beverages, it is fermented and distilled, and carbon dioxide and ethanol or beverages are produced. The unfermented portion of the corn grain (i.e., protein, lipids, fiber, and ash) is a coproduct from this production. This product is often split into a distilled grains portion and a solubles portion. The distilled grains may be dried and sold as distillers dried grains (DDG). However, the solubles may also be added to the distilled grain and dried and in that case, distillers dried grains with solubles (DDGS) is produced (Shurson and Alghamdi, 2008; Belyea et al., 2010; Liu, 2011; Stein, 2012). Distillers dried grains and DDGS contain 9 to 14% crude fat, but in some ethanol plants, crude fat is centrifuged off the solubles before solubles are added to the distilled grains and a low-fat DDGS is then produced. This product contains between 5 and 8% crude fat, but at this time there are no published reports about the nutritive value of low-fat DDGS. It is, however, expected that the concentration of digestible and metabolizable energy in low-fat DDGS is less than in conventional DDGS.

The fat in DDGS may also be extracted using a solvent extraction procedure and the resulting product, which contains between 2 and 6% crude fat, is called deoiled DDGS (Jacela et al., 2011). The energy value in deoiled DDGS is considerably less than in conventional DDGS, but the concentration and digestibility of AA are within the range of values reported for conventional DDGS (Jacela et al., 2011).

Conventional DDGS contains between 25 and 30% CP, but because the majority of the protein originates from corn, it is low in lysine (0.5-1.0%) and tryptophan (0.10-0.34) (Spiehs et al., 2002; Stein and Shurson, 2009; Liu, 2011). The concentration of lysine is more variable than the concentration of most other AA in DDGS (Shurson and Alghamdi, 2008) because overheating sometimes destroys lysine in DDGS or converts it into other compounds that cannot be used for protein synthesis (Fastinger and Mahan, 2006; Pahm et al., 2008a,b; Stein and Shurson, 2009; see also Chapter 2). However, destruction of lysine due to overheating is less of a problem in DDG than in DDGS because addition of the solubles to the distilled grains increases the risk of creating Maillard reactions and thereby destroying lysine (Pahm et al., 2008b). Maillard reactions in DDGS also reduce the apparent and standardized ileal digestibility of lysine and there is, therefore, more variability in the digestibility of lysine in DDGS than in the digestibility of other AAs (Fastinger and Mahan, 2006; Stein and Shurson, 2009).

The concentration of neutral detergent fiber (NDF) is between 30 and 35% in DDGS (Spiehs et al., 2002), but because of the relatively high concentration of fat and protein in DDGS, the concentration of digestible and metabolizable energy in DDGS is similar to that in corn (Pedersen et al., 2007; Stein et al., 2009). The concentration of P in DDGS is between 0.37 and 0.88% (Shurson and Alghamdi, 2008). During production of DDGS, some of the phytate bonds are hydrolyzed, possibly due to the presence of small amounts of phytase produced by the yeast that is added to aid in the fermentation process (Liu, 2011). The proportion of total P that is bound to phytate in DDGS, therefore, is only 43%, whereas 73% of the P in ground corn is bound to phytate (Liu and Han, 2011). As a consequence, the digestibility of P in DDGS is between 50 and 70%, whereas the digestibility of P in corn is < 40% (Pedersen et al., 2007; Almeida and Stein, 2010, 2012). However, the digestibility of P in corn can be improved by microbial phytase but the high digestibility of P in DDGS is not further improved by microbial phytase (Almeida and Stein, 2010, 2012).

Concentrations of most minerals in DDGS are approximately threefold greater than in corn, but the concentrations of S, Na, and Ca are increased much more than threefold in DDGS compared with corn because of the addition of exogenous sources of these minerals during production of DDGS (Liu and Han, 2011). The greater concentrations of S in DDGS compared with corn may result in formulation of diets that contain considerably more S than corn–soybean meal diets, but neither palatability nor performance seems to be affected by the concentration of S in DDGS (Kim et al., 2012).

Several reviews that describe the consequences of including DDGS in diets fed to growing and reproducing swine have been published (Shurson et al., 2004; Patience et al., 2007; Shurson and Alghamdi, 2008; Stein and Shurson, 2009; Stein, 2012). For lactating sows, up to 30% DDGS may also be included in the diet without reducing sow or litter performance (Hill et al., 2008; Song et al., 2010) and diets fed to gestating sows may contain up to 44% DDGS (Thong et al., 1978). In diets fed to weanling pigs, DDGS may be included at levels as high as 20 to 30% without reducing growth performance (Whitney and Shurson, 2004; Almeida and Stein, 2010; Jones et al., 2010a) although negative effects of adding 20% DDGS to diets fed to weanling pigs have also been reported (Kim et al., 2012).

For growing-finishing pigs, numerous experiments have documented that up to 30% DDGS can be included in the diets without reducing pig growth performance (Widyaratne and Zijlstra, 2007; Widmer et al., 2008; Xu et al., 2010a; Yoon et al., 2010; McDonnell et al., 2011). There are, however, also reports of reduced growth performance of growing-finishing pigs when up to 30% DDGS is included in the diet (Whitney et al., 2006; Linneen et al., 2008; Leick et al., 2010; Kim et al., 2012). In a recent experiment, a slight negative effect on average daily gain, but not on feed intake or feed efficiency, was reported when up to 45% DDGS was added to diets fed to growing-finishing pigs (Cromwell et al., 2011).

Effects of DDGS on carcass composition and quality have been reported from numerous experiments. In approximately 50% of all reported experiments, a reduction in dressing percentage has been observed, whereas that is not the case in the other 50% (Stein and Shurson, 2009). Very few changes in lean meat percentage and backfat thickness have been reported, but inclusion of DDGS in diets fed to finishing pigs has consistently resulted in increased deposition of unsaturated fatty acids in the adipose tissue (Benz et al., 2010; Leick et al., 2010; Xu et al., 2010a,b; Cromwell et al., 2011). The increased concentration of unsaturated fatty acids results in pigs producing softer bellies, which may reduce bacon slicing quality (Whitney et al., 2006; Leick et al., 2010; Cromwell et al., 2011). However, belly firmness can be partially restored if DDGS is withdrawn from the diets for 3 to 4 weeks before slaughter (Xu et al., 2010b).

Feed intake has been reduced in some, but not all, experiments in which DDGS has been included in diets fed to weanling or growing-finishing pigs (Stein and Shurson, 2009; Stein, 2012). The reduced feed intake is likely a result of pigs preferring to eat diets containing no DDGS compared with diets containing DDGS (Seabolt et al., 2010; Kim et al., 2012).

Other consequences of using DDGS in diets fed to pigs include an increase in the volume of manure because of the reduced DM digestibility in DDGS compared with corn and soybean meal (Shurson et al., 2004; McDonnell et al., 2011). The concentration of N excreted from the pigs may also increase if DDGS is used (McDonnell et al., 2011), but the extent of this increase depends on the diet formulation technique. In contrast, the concentration of P may decrease because of the greater digestibility of P in DDGS compared with corn (Hill et al., 2008; Almeida and Stein, 2010).

High-Protein Distillers Dried Grains, High-Protein Distillers Dried Grains with Solubles, and Corn Germ

In some ethanol plants, corn is dehulled and degermed before it is fermented and distilled. The purpose of this process is to reduce the concentration of unfermentable materials (i.e., fiber and fat) and have a product with a greater starch concentration enter fermentation to increase the yield of ethanol from the process (Rausch and Belyea, 2006; Rosentrater et al., 2012). The distilled grain that is produced from this process has a greater concentration of CP (40-48%) and ash than the conventional distilled grains, but the concentration of lipids is reduced to < 6% (Widmer et al., 2007; Kim et al., 2009; Jacela et al., 2010). The solubles are usually not added to the distilled grain if this process is used, and the dried grain is, therefore, called high-protein distillers dried grains (HP-DDG), but if the solubles are added to the dried grains, high-protein distillers dried grains with solubles (HP-DDGS) is produced (Stein, 2012). The concentration of digestible and metabolizable energy in HP-DDG is greater than in corn and in traditional DDGS, and the digestibility of AA is similar to that in conventional DDGS (Widmer et al., 2007; Kim et al., 2009; Jacela et al., 2010). The concentration of P in HP-DDG is less than in traditional DDGS, but the digestibility of P in HP-DDG is similar to that in DDGS (Widmer et al., 2007; Almeida and Stein, 2012). As is the case for DDGS, the digestibility of P in HP-DDG is only slightly increased if microbial phytase is added to the diet (Almeida and Stein, 2012).

If HP-DDG is included in diets that are correctly balanced for essential AAs, HP-DDG may be included by at least 40% in diets fed to growing pigs (Widmer et al., 2008) and it may replace all the soybean meal in diets fed to finishing pigs (Widmer et al., 2008; Kim et al., 2009). At this time, there are no published data on the inclusion of HP-DDG in diets fed to weanling pigs, gestating sows, or lactating sows.

Corn germ is produced in the initial degerming of the grain and may also be used as a feed ingredient in diets fed to pigs. This product contains 16-20% crude fat, approximately 15% CP, and has a relatively high concentration of fiber (Widmer et al., 2007). The concentration of digestible and metabolizable energy in corn germ is similar to that in corn (Widmer et al., 2007). Corn germ contains > 1.1% P, but the majority is bound in the phytate complex and the digestibility of phosphorus in corn germ is, therefore, low (Widmer et al., 2007; Almeida and Stein, 2012). However, inclusion of microbial phytase in diets containing corn germ will increase the digestibility of P to a level that is close to that in HP-DDG and DDGS (Almeida and Stein, 2012). Corn germ may be included in diets fed to growing-finishing pigs at levels up to 30% without affecting pig growth performance (Lee, 2011). However, because of the relatively high concentration of unsaturated oil in corn germ, greater concentrations of unsaturated fatty acids will be deposited in backfat and belly fat of pigs fed diets containing corn germ, and belly softness will be increased (Lee, 2011). There are no published data on effects of including corn germ in diets fed to weanling pigs, gestating sows, or lactating sows.

Corn Gluten Meal, Corn Gluten Feed, Corn Germ Meal, and Hominy Feed

Corn gluten meal is a coproduct of the wet milling industry where it is produced after most of the starch and germ and some of the fiber have been removed (Stock et al., 2000). All the protein is, however, left in the product and corn gluten meal contains around 60% CP and has a low content of NDF (de Godoye et al., 2009; Almeida et al., 2011). The digestibility of most AAs in corn gluten meal is greater than in corn for growing-finishing pigs (Knabe et al., 1989; Almeida et al., 2011), and the concentration of DE and ME in corn gluten meal is greater than in corn (Young et al., 1977).

The balance of AA in corn gluten meal is not ideal relative to the requirement of pigs and there is relatively little corn gluten meal used in diets fed to pigs. However, if corn gluten meal–containing diets are fortified with crystalline lysine and tryptophan, diets that are balanced in essential AA may be formulated. Up to 15% corn gluten meal may be included in diets fed to weanling pigs without impacting pig performance (Mahan, 1993).

Corn gluten feed is also a coproduct of the wet milling industry and is the part of the corn kernel that remains after the extraction of most of the starch, germ, and gluten for production of corn starch or corn syrup. It mainly consists of corn bran, corn germ, and steep liquor (Honeyman and Zimmerman, 1991; Stock et al., 2000). Corn gluten feed is, therefore, a high-fiber feed ingredient that contains > 30% NDF and 20-25% CP. The digestibility of most AA in corn gluten feed is not different from the digestibility of AA in corn (Almeida et al., 2011). The concentration of DE and ME in corn gluten feed fed to growing-finishing pigs is less than in corn (Yen et al., 1974; Young et al., 1977), but when fed to gestating sows, the DE and ME in corn gluten feed are similar to the DE and ME in corn (Honeyman and Zimmerman, 1991). Corn gluten feed is not commonly used in diets fed to weanling or growing pigs, but it may be included in large quantities in diets fed to gestating sows without affecting sow or litter performance (Honeyman and Zimmerman, 1990).

Corn germ may be produced from wet milling where germ is separated from the corn kernel during the initial steps before starch is removed (Stock et al., 2000) or as a result of dry milling before production of corn meal, corn grits, or other corn products. The germ undergoes fat extraction and the oil is used for human consumption. The resulting defatted corn germ is called corn germ meal and contains usually < 3% crude fat (Stock et al., 2000; Weber et al., 2010). Corn germ meal is, therefore, quite different in composition from corn germ. Corn germ meal contains > 50% NDF and approximately 20% CP (Weber et al., 2010). The digestibility of most AA in corn germ meal fed to growing-finishing pigs is slightly less than in corn (Almeida et al., 2011). Inclusion of up to 38% corn germ meal in diets fed to growing pigs may not affect pig growth performance, but feed efficiency may be reduced (Weber et al., 2010).

Hominy feed is a coproduct from the dry-milling industry after production of corn flour, corn grits, or pearl hominy and consists of corn bran, broken kernels, germ residue after oil extraction, and fractions of corn germ, pericarp, and endosperm (Larson et al., 1993; Stock et al., 2000). Hominy feed contains 6-10% CP and > 4% ether extract. The concentration of starch and NDF can vary, but most sources of hominy feed contain > 50% starch and < 30% NDF (Larson et al., 1993). The energy value of hominy feed to pigs is similar to that of corn (Stanley and Ewan, 1982) and the digestibility of most AA in hominy feed is less than that in corn (Almeida et al., 2011). Hominy feed is palatable and easily consumed by pigs and it may be included in diets fed to all groups of pigs. There are, however, no published titration experiments designed to determine the optimum inclusion level of hominy feed in diets fed to different categories of pigs.

SOYBEAN PRODUCTS

Full-Fat Soybeans

Soybeans produced in the United States typically contain 15-20% ether extract and 35-37% CP (Grieshop et al., 2003; Karr-Lilienthal et al., 2005). Because of the presence of trypsin inhibitors in soybeans, they need to be heat-treated before being fed to pigs, which is most often accomplished by extruding the beans prior to use (Baker, 2000). The concentration of trypsin inhibitors in raw soybeans is approximately 35 trypsin inhibitor units, but heating can reduce this level to < 4 units (Lallès, 2000; Goebel and Stein, 2011a). Full-fat soybeans may be fed as intact full-fat beans or as dehulled full-fat beans. Intact full-fat soybeans contain 8-12% NDF, whereas dehulled full-fat soybeans contain approximately 5% NDF. The concentration of total carbohydrates in intact soybeans is 35-40% with approximately 15% being nonstructural carbohydrates (primarily sucrose and oligosaccharides) and the rest being structural polysaccharides such as acidic polysaccharides, arabinogalactans, and cellulosic material (Karr-Lilienthal et al., 2005). The concentration of starch in soybeans is < 1.0%.

During recent years, breeding efforts have resulted in high-protein soybeans being produced. These soybeans contain 44-48% CP whereas conventional beans contain 35-37% CP (Cervantes-Pahm and Stein, 2008; Baker et al., 2010). The increased concentration of CP in high-protein soybeans is achieved at the expense of ether extract and certain carbohydrates and there is a negative correlation between CP concentration and ether extract in soybeans (Yaklich, 2001). There is also often a reduced concentration of sucrose and NDF in high-protein soybeans compared with conventional soybeans (Hartwig et al., 1997; Cervantes-Pahm and Stein, 2008).

Conventional soybeans contain approximately 15% nonstructural carbohydrates such as sucrose, uronic acid, oligosaccharides, and free sugars (Grieshop et al., 2003; Karr-Lilienthal et al., 2005). The concentration of sucrose in conventional soybeans is usually between 4 and 8% and the concentration of oligosaccharides (raffinose, stacchyose, and verbascose) is between 4 and 7% (Grieshop et al., 2003; Cervantes-Pahm and Stein, 2008; Goebel and Stein, 2011a). Because of the negative nutritive effects of oligosaccharides in diets fed to young animals, varieties of soybeans that contain < 2% oligosaccharides have been selected (van Kempen et al., 2006; Baker and Stein, 2009; Baker et al., 2010). Soybean meal produced from these low-oligosaccharide varieties is believed to be better tolerated by young pigs than conventional soybean meal, but at this point, there are no data published to verify this hypothesis.

Soybean Meal

Solvent-Extracted Soybean Meal

Most soybeans are fed to pigs in the form of defatted soybean meal after removal of the oil via solvent extraction. Soybeans are cleaned and flaked prior to oil extraction and the extracted oil is most often used for industrial or food applications, but the majority of the defatted meal is used in livestock feeding. The defatted meal is desolventized to remove the residual hexane and then steam cooked to inactivate trypsin inhibitors (Witte, 1995). A urease test is used as an indicator of the level of trypsin inhibitors in the meal and a pH rise of < 0.2 on the standard urease test is indicative of elimination of the trypsin inhibitors (Witte, 1995). The final step in production of soybean meal is grinding to a common particle size. Soybean meal produced via solvent extraction usually contains < 3% ether extract (Wang and Johnson, 2001; Karr-Lilienthal et al., 2005).

The beans used to produce soybean meal may be intact beans or they may be dehulled prior to flaking (Ericson, 1995). These two processes result in production of either hulled or dehulled soybean meal. Dehulled soybean meal contains between 46 and 48% CP (Grieshop et al., 2003; Baker and Stein, 2009) and 6 to 8% NDF, whereas hulled soybean meal contains 42-44% CP and 12-14% NDF (Cervantes-Pahm and Stein, 2008).

Mechanically Expelled Soybean Meal

As an alternative to solvent extraction, soybeans may also be defatted via mechanical extraction or expelling of the oil using a continuous screw press. Less than 1% of all the soybean meal produced in the United States is produced using this procedure (Ericson, 1995). Expelled soybean meal is often heat treated by extrusion and it is then called "extruded-expelled soybean meal" (Wang and Johnson, 2001; Woodworth et al., 2001; Baker and Stein, 2009). Because mechanical oil extraction is less efficient than solvent extraction, the concentration of ether extract is usually 5-10% in extruded-expelled soybean meal (Wang and Johnson, 2001; Karr-Lilienthal et al., 2006). Soybeans used for extrusion-expelling are usually not dehulled and extruded-expelled soybean meal, therefore, contains more NDF and less protein than solvent-extracted dehulled soybean meal (Karr-Lilienthal et al., 2006; Baker and Stein, 2009).

Enzyme-Treated and Fermented Soybean Meal

The presence of antigens in conventional soybean meal precludes soybean meal from being included in large concentrations in diets fed to young pigs (Li et al., 1990). However, antigens may be removed from soybeans via enzyme treatment or via fermentation. Both processes also result in removal of sucrose and most of the oligosaccharides in the soybean meal and enzyme treatment or fermentation, therefore, results in production of soybean meal that has a low concentration of antigens and oligosaccharides (Cervantes-Pahm and Stein, 2010; Goebel and Stein, 2011b). The removal of sucrose and oligosaccharides from enzyme-treated or fermented soybean meal results in a gross composition that is different from that of conventional soybean meal (Cervantes-Pahm and Stein, 2010). The concentration of CP in enzyme-treated and fermented soybean meal is between 52 and 57% and the concentration of NDF is also increased compared with conventional soybean meal (Cervantes-Pahm and Stein, 2010; Goebel and Stein, 2011b).

Because of the removal of antigens and oligosaccharides in fermented soybean meal and enzyme-treated soybean meal, it is believed that these two sources of soybean meal may be used in diets fed to weanling pigs without causing digestive difficulties as is the case for conventional soybean meal. Recent data have confirmed that both sources of soybean meal may be used in diets fed to pigs right after weaning as replacement for animal proteins (Yang et al., 2007; Jones et al., 2010b; Kim et al., 2010).

Soy Protein Concentrate and Soy Protein Isolate

Soy protein concentrate is produced from dehulled and defatted soybean meal by removing the water- or alcohol-soluble nonprotein components, including the soluble carbohydrates (Lusas and Rhee, 1995; Endres, 2001). By definition, soy protein concentrate contains a minimum of 65% CP (DM basis; Lusas and Rhee, 1995; Endres, 2001). It may be produced by acid leaching, extraction with aqueous alcohol, or by denaturing the protein with moist heat before extraction with water (Endres, 2001). Soy protein concentrate may be used in diets fed to weanling pigs as replacements for animal proteins without negatively impacting performance (Lenehan et al., 2007; Yang et al., 2007). Likewise, soy protein concentrate may also be used as a protein source in milk replacers (Endres, 2001).

Soy protein isolate is produced from dehulled and defatted soybeans by removing most of the nonprotein constituents in the product (Endres, 2001). The protein is solubilized at neutral and slightly alkaline pH and the extract is then precipitated by acidification to obtain the protein isolate (Berk, 1992). On a DM basis, soy protein isolate contains > 90% CP (Endres, 2001). Soy protein isolate is relatively expensive and is usually not used in diets fed to pigs in commercial production, but it may be included in semisynthetic diets fed to pigs used for research. The AA in soy protein isolate have a high digestibility that is similar to that of AA in casein (Cervantes-Pahm and Stein, 2010).

Soybean Hulls

Most soybeans are dehulled prior to oil extraction and the defatted meal is subsequently sold as dehulled soybean meal. The soybean hulls that are generated during this process are marketed separately and may be included in diets fed to pigs. Soybean hulls contain > 50% NDF and between 12 and 15% CP (Kornegay, 1981; Jacela et al., 2007; Barbosa et al., 2008). The concentration of metabolizable energy in soybean hulls is relatively low because of the high concentration of NDF (Jacela et al., 2007) and it is, therefore, recommended that the inclusion of soybean hulls in diets fed to growing-finishing pigs does not exceed 15% (Kornegay, 1981). It is also recognized that the digestibility of some amino acids may be reduced if soybean hulls are included in the diets (Dilger et al., 2004).

CRUDE GLYCERIN

The production of biodiesel has expanded during recent years and crude glycerin is a byproduct from biodiesel production. Approximately 80 g of crude glycerin is generated for every liter of biodiesel produced (Thompson and He, 2006; Sharma et al., 2008). The chemical analysis of crude glycerin can be quite variable, with the main components being glycerin, moisture, and ash with trace amounts of fatty acids and methanol. Typical composition ranges are 78-85% glycerin, 8-15% water, 2-10% salt (NaCl or KCl), 0.5% free fatty acids, and ≤ 0.5% methanol (Hansen et al., 2009; Kerr et al., 2009). Crude glycerin may be used as an energy source in diets fed to pigs (Bartelt and Schneider, 2002; Lammers et al., 2008b; Zijlstra et al., 2009), and the energy value of glycerin is directly related to its glycerin, fatty acid, and methanol content (Kerr et al., 2009). Glycerin may be included in diets fed to all categories of pigs and does not influence pig performance, carcass composition, or meat quality (Groesbeck et al., 2008; Lammers et al., 2008a; Della Casa et al., 2009; Hansen et al., 2009; Zijlstra et al., 2009). However, depending on the level and type of salt in the crude glycerin, feed formulations may need to be adjusted to avoid excessive concentrations of Na, K, or Cl. Methanol also warrants special consideration because methanol is a potentially toxic compound. In the United States, crude glycerin can be fed to nonruminant animals at levels up to 10% of the complete diet as long as it contains not less than 80% glycerin, not more than 15% water, not more than 0.15% methanol, less than 8% salt, less than 0.1% sulfur, and less than 5 ppm heavy metals (AAFCO, 2010). In Germany, regulations allow 0.5% methanol in crude glycerin (Normenkommission fur Einzelfuttermittel im Zentralausschuss der Deutschen Landwirtschaf, 2006).

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10

Nonnutritive Feed Additives

INTRODUCTION

Nonnutritive feed additives are additives that are not required by pigs, but they may be included in swine diets. Of these, the antimicrobial agents are believed to be the most commonly used. Antimicrobial agents and anthelmintics are defined as "drugs" by the U.S. Food and Drug Administration (FDA). Thus, their usage levels, allowable combinations, and periods of withdrawal prior to slaughter are regulated by the FDA.

In addition to the antimicrobial agents and anthelmintics, other additives may be included in diets fed to swine. These additives may or may not have proven positive effects on pig performance. Some of these additives (acidifiers, direct-fed microbials, nondigestible oligosaccharides, and plant extracts) were reviewed by Stein (2007), and that review is updated in this chapter.

ANTIMICROBIAL AGENTS

The effects of adding subtherapeutic doses of antimicrobial agents to diets fed to pigs are well documented (Cromwell, 2001) and currently, 11 antibiotics and 5 chemotherapeutics are approved for use in diets fed to swine in the United States (Cromwell, 2011). All the chemotherapeutics require withdrawal from the feed prior to slaughter, but that is not the case for the antibiotics (Cromwell, 2011). Although there are wide variations among reported experiments in the responses to antimicrobials, on average, inclusion of antimicrobials in diets fed to weanling pigs improves growth rate by 16.4% and feed efficiency by 6.9% while the improvements are 10.6 and 4.5%, respectively, for growing pigs (Cromwell, 2001, 2011). Antimicrobials are less effective in finishing pigs than in younger pigs, and for the entire growing-finishing period, daily gain improves on average by 4.2% and feed efficiency improves by 2.2% if antimicrobials are included in the diet (Cromwell, 2001). Mortality is usually reduced if antimicrobials are added to the diet (from 4.3 to 2.0%), but the reduction may be greater if the disease pressure is high (Cromwell, 2011). If included in diets fed to sows, antimicrobials may improve farrowing rate and the number of liveborn pigs, and pig weaning weights and pig survival may also be improved if antimicrobials are used in diets fed to lactating sows (Cromwell, 2011).

The mechanism of action of antimicrobials is not fully understood, but there are numerous reports indicating that antimicrobials have a disease-reducing effect on pigs (Ding et al., 2006; Hays, 2011). This effect is likely asserted by improving the immunity of the pigs and by controlling intestinal pathogens. Antimicrobials may also improve energy and nutrient digestibility in diets fed to pigs (Roth and Kirchgessner, 1993; Gaines et al., 2005; Agudelo et al., 2007; Stewart et al., 2010), which results in more nutrients being available for tissue synthesis. The improved digestibility of nutrients and energy may be a result of changes to the intestinal microbial population (Stewart et al., 2010), but reduced thickness of the gut wall may also be observed in pigs fed diets containing antimicrobials.

ANTHELMINTICS

Internal parasites may reduce growth performance of pigs and result in significant economic losses in swine production (Myers, 1988; Urban et al., 1989; Jacela et al., 2009) and in extreme cases, infestation may lead to carcass condemnation. Parasite control is, therefore, an important part of a herd health protocol and parasites may be controlled by anthelmintics, which are also known as "dewormers." There are currently eight different anthelmintics approved for commercial use in the United States, and withdrawal periods between 24 hours and 21 days have been issued for six of the eight products (Jacela et al., 2009).

The most commonly known internal parasites are roundworm, threadworm, kidney worm, whipworm, and lungworm. These parasites may be controlled by inclusion of one of the approved anthelmintics in the diet (or in some cases in the drinking water). Injectable formulations are also available for some of the products.

The eight commercial anthelmintics that are currently approved for use in swine belong to six different groups of drugs: dichlorvos, ferbendazole, ivermectin, levamisole, piperazine, and pyrantel tartrate (Jacela et al., 2009). All products are effective against all or some of the internal parasites, but ivermectin is also effective against external parasites such as lice and mange. In addition to its anthelmintic activities, dichlorvos may also increase the number of live-born pigs if included in diets fed to gestating sows (Siers et al., 1976). Colostrum lipid concentration and litter weight gain also were improved in pigs from sows fed dichlorvos (Siers et al., 1976; Young et al., 1979). In addition to the direct effects of anthelmintics in reducing the infestations with parasites, treatment with anthelmintics may also improve pig live weight gain and feed efficiency (Zimmerman et al., 1982; Southern et al., 1989; Urban et al., 1989). This growth-promoting effect of some of the anthelmintics is likely an indirect effect of reducing the parasite infection.

ACIDIFIERS

Products recognized as diet acidifiers include organic acids, inorganic acids, and salts of acids. Addition of organic acids such as fumaric acid (Falkowski and Aherne, 1984; Giesting and Easter, 1985; Radecki et al., 1988; Giesting et al., 1991), formic acid, citric acid, and propionic acid (Falkowski and Aherne, 1984; Henry et al., 1985; Manzanilla et al., 2004) has improved pig performance. Addition of butyrate may result in an improved feed efficiency (Manzanilla et al., 2006), possibly by regulating responses to an immune stimulus in weanling pigs (Weber and Kerr, 2008), but effects on performance are often small (de Lange et al., 2010).

Some inorganic acids, such as phosphoric acid or hydrochloric acid, may also improve pig performance (Mahan et al., 1996); other inorganic acids, such as sulfuric acid, reduce pig performance. Usually, between 1 and 2% of organic acids needs to be included to obtain a positive response, but for inorganic acids, < 0.5% may be needed.

Positive responses to the inclusion of salts of acids have been reported from experiments in which weanling pig diets were supplemented with sodium formate (Kirchgessner and Roth, 1987), calcium formate (Kirchgessner and Roth, 1990; Pallauf and Hüter, 1993), and potassium diformate (Overland et al., 2000; Canibe et al., 2001). The inclusion rate of these products usually needs to be > 1%.

Commercial acidifiers may contain combinations of both organic and inorganic acids and inclusion levels are generally low. Because the amounts of specific acids included in these products are often proprietary, the effects of the combination products are difficult to predict, but positive responses to such blends have been reported (Walsh et al., 2007a,b). Addition of an acidifier to the diet of growing-finishing pigs may also reduce urinary pH, which may lead to a reduction in the ammonia emission from swine production (van Kempen, 2001).

DIRECT-FED MICROBIALS

Direct-fed microbials are sometimes also called probiotics and may be divided into three main categories:

1. *Bacillus* (Gram-positive spore-forming bacteria);
2. Lactic acid–producing bacteria (*Lactobacillus*, *Bifidobacterium*, *Enterococcus*);
3. Yeast.

Probiotics are defined as microorganisms that confer a health benefit on the host if administered in the correct amount (Kenny et al., 2011). Among the organisms most often used in this group are *Lactobacillus* spp., *Enterococci faecium*, *Bacillus lichiniformis*, *Bacillus subtillis*, *Bifidobacterium bifidum*, *Bifidobacterium thermophilus*, and others (Jonsson and Conway, 1992).

Probiotic cultures will have a positive effect on pig performance only if the following conditions occur:

- The culture is able to establish itself in the gastrointestinal tract of the animal.
- The culture has a high growth rate.
- The culture excretes metabolites that have a suppressing effect on pathogens.
- The culture can be grown under commercial conditions.
- The culture can be stabilized and has the ability to survive in feed.

The proposed mechanism of action of direct-fed microbials is that they colonize the intestinal tract and dominate the native intestinal microflora, which prevents intestinal pathogens from colonizing (competitive exclusion).

Many direct-fed microbials contain lactic acid–producing bacteria. They are used to prevent the reduction in the enteric lactic acid–producing bacteria that is often observed during the immediate postweaning period (Doyle, 2001). Positive responses to inclusion of lactic acid–producing bacteria in diets fed to weanling pigs have been reported from a number of experiments (Apgar et al., 1993; Zani et al., 1998; Kyriakis et al., 1999). Growth performance has also been improved by inclusion of *Bacillus* organisms in diets fed to growing-finishing pigs (Davis et al., 2008). Inclusion of *Enterococcus faecium* to diets fed to lactating sows may reduce preweaning scouring and mortality of pigs (Taras et al., 2006), and administration of *Enterococcus faecium* to pigs from birth to weaning may reduce scouring and improve pig weight gain (Zeyner and Boldt, 2006).

Yeast cultures may be added to pig diets as live yeast or dried yeast, and there is no evidence that one form is better than the other. Yeast and yeast products may contain amino acids, enzymes, nucleotides, vitamins, saccharides, minerals, and other metabolites. Some authors (Mathew et al., 1998; van Heugten et al., 2003; van der Peet-Schwering et al., 2007; Shen et al., 2009) have reported positive performance responses to the inclusion of yeast in diets fed to weanling or growing pigs, but others have reported that dietary yeast results in no change in pig growth performance (Kornegay et al., 1995; Sauerwein et al., 2007). Likewise, inclusion of probiotics to sow diets may increase productivity (Kim et al., 2008, 2010), but that is not always the case (Veum et al., 1995; Jurgens et al., 1997). The positive responses of yeast in diets fed to swine may be because yeast is able to suppress the concentration of coliform bacterial populations in the intestinal tract of pigs (White et al., 2002). However, the response of microbial populations to adding yeast or yeast cultures to diets fed to weanling or growing pigs has been inconsistent (Mathew et al., 1998; van Heugten et al., 2003; van der Peet-Schwering et al., 2007; Shen et al., 2009).

NONDIGESTIBLE OLIGOSACCHARIDES

This group of additives is also called prebiotics or nutraceuticals and includes readily fermentable, but indigestible, oligosaccharides such as fructo-oligosaccharides, β-glucans, galacto-oligosaccharides, and *trans*-galacto-oligosaccharides. These oligosaccharides are believed to improve pig performance by stimulating the proliferation of *Bifidobacteria* in the large intestine, which in turn increases the concentration of lactic acid and reduces colonic pH (Houdijk et al., 2002). It is thought that only beneficial bacteria (e.g., bifidobacteria and lactobacilli) can ferment the oligosaccharides, whereas pathogens such as *Salmonella* and *Escherichia coli* cannot (Flickinger et al., 2003). Oligosaccharides may also improve intestinal secretions and growth of the digestive mucosa and a number of different fiber fractions have been tested for their ability to enhance pig growth and suppress pathogenic bacteria colonization. It is also believed that galacto-oligosaccharides stimulate beneficial bacterial growth in the large intestine and improve intestinal health (Smiricky-Tjardes et al., 2003). For example, *Bifidobacteria* may suppress the growth of pathogenic bacteria (i.e., *E. coli*) by stimulating the production of acetate, which further decreases the pH and reduces the incidence of diarrhea (Mosenthin et al., 1999). Thus, dietary oligosaccharides are believed to stimulate the growth of beneficial bacteria in the intestinal tract, which then results in improved nutrient utilization or reduced pathogenic load in the intestines.

Other components of fiber (i.e., mannanoligosaccharides) may improve health and performance. Results from several experiments indicated that pig growth performance may be improved by inclusion of mannanoligosaccharides in the diet (LeMieux et al., 2003; Rozeboom et al., 2005). The mode of action may be that the mannanoligosaccharides bind to specific lectin ligands on the surface of epithelial cells, thus preventing pathogenic bacteria from binding to these ligands, resulting in a "flushing" effect on pathogenic bacteria (LeMieux et al., 2003; Rozeboom et al., 2005). It has also been suggested that mannanoligosaccharides enhance the immune system by directly evoking an antibody response (Davis et al., 2004).

PLANT EXTRACTS

Extracts of herbs and spice preparations have been valued since historical times for their antimicrobial properties. The biologically active component of herbs and spices is often the so-called "essential oil" (Zaika et al., 1983), although this is not always the case (Deans and Ritchie, 1987). The activity of plant extracts is influenced by numerous factors, such as the genotype of the plant and the growing conditions (Deans and Richie, 1987; Piccaglia et al., 1993). Essential oils may exert their antimicrobial effects by causing changes in lipid solubility at the surface of the bacteria (Dabbah et al., 1970); however, other mechanisms, such as disintegration of the outer membrane, have also been demonstrated.

The most common botanicals used in diets fed to swine are garlic, oregano, thymol, and carvacrol. Although these compounds have strong antimicrobial properties in vitro, there is little evidence that they enhance pig performance. In fact, Namkung et al. (2004) reported reduced pig performance when a combination of oregano, thyme, and cinnamon was added to diets of weanling pigs, and no benefits were found in studies using other combinations of botanicals (Manzanilla et al., 2004, 2006; Insley et al., 2005).

Mixtures of plant extracts have been proposed as alternatives to in-feed antibiotics for pigs. However, there is currently insufficient evidence in carefully controlled experiments with pigs to support this concept.

EXOGENOUS ENZYMES

Carbohydrases

Adding carbohydrate-degrading enzymes to diets containing barley, wheat, or oats may improve fiber digestibility, although growth performance is not always affected (Inborr et al., 1993; Nonn et al., 1999; Thacker and Campbell, 1999; Carneiro et al., 2008; O'Shea et al., 2010). The major nonstarch polysaccharide in barley is β-glucan and the major nonstarch polysaccharide in wheat is arabinoxylan. It is, therefore, expected that addition of β-glucanase may improve the utilization of barley and barley byproducts, whereas addition of xylanase may improve the feeding value of wheat and wheat byproducts. However, supplementation of an enzyme cocktail (cellulase, galactanase, mannanase, and pectinase) to a wheat-based diet fed to 6-kg pigs may improve pig growth performance (Omogbenigun et al., 2004). Likewise, addition of xylanase to a wheat-based diet for weanling pigs may reduce the incidence of postweaning colitis (Newbold and Hillman, 2011).

Limited research has been reported on the impact of exogenous enzymes on nutrient digestibility or pig growth performance when pigs are fed corn-based diets. Supplementation of β-glucanase to a corn-soybean meal–based diet had no impact on dry matter (DM), energy, or crude protein (CP) digestibility in 6-kg pigs (Li et al., 1996), and addition of β-mannanase to a corn-soybean meal–based diet had no effect on DM, energy, or N digestibility in 93-kg barrows (Pettey et al., 2002). In contrast, Ji et al. (2008) reported that a β-glucanase-protease enzyme blend added to a corn-soybean meal–based diet improved total tract digestibility of DM, energy, CP, total dietary fiber, and phosphorus. Likewise, β-mannanase improved feed efficiency in 6- and 14-kg pigs, and improved gain and feed efficiency when fed from 23 to 110 kg (Pettey et al., 2002). Addition of xylanase to a diet based on various wheat byproducts also improved energy, and DM digestibility when fed to growing-finishing pigs and the digestibility of some indispensable AA was improved as well (Nortey et al., 2007, 2008). It was also observed that the gain:feed ratio of growing pigs fed diets containing wheat byproducts was improved if xylanase was included in the diet compared with pigs fed the control diet without xylanase (Nortey et al., 2007). These observations confirm the hypothesis that xylanase may be effective in improving the nutrient and energy digestibility in diets based on wheat or wheat byproducts. A carbohydrase enzyme mixture (α-1,6-galactosidase and β-1,4-mannanase) may also improve feed efficiency if added to a corn-soybean meal–based diet fed to weanling pigs (Kim et al., 2003).

Addition of enzymes to diets containing 30% distillers dried grains with solubles (DDGS) may increase growth performance of nursery pigs (Spencer et al., 2007), but that is not always the case (Jones et al., 2010a). Supplementing exogenous enzymes to a corn-soybean meal–DDGS based diet fed to finishing pigs did not enhance pig growth performance (Jacela et al., 2010b), but Yoon et al. (2010) reported improved gain and nutrient digestibility in growing-finishing pigs when mannanase was supplemented to diets containing up to 15% DDGS.

The impact of exogenous enzymes on gaseous emissions is poorly understood and results have been conflicting (Garry et al., 2007a,b; O'Shea et al., 2010). At this point it is, therefore, not possible to clearly predict effects of enzymes on odor or ammonia emissions.

Phosphatases

Effects of inclusion of a phosphatase (also called "phytase") to diets fed to pigs have been documented in numerous experiments (Adeola et al., 2004, 2006; Almeida and Stein, 2010). Phosphatase enzymes hydrolyze phosphorus from phytate (Konietzny and Greiner, 2002) starting at the 3- or the 6-position on the phytate molecule. Phytase activity (FTU) is defined as the amount of enzyme activity that liberates 1 μmol of inorganic orthophosphate per minute from 0.0051 mol/L sodium phytate at pH 5.5 and 37°C (Engelen et al., 1994). The current "standard" assay for phytase activity is AOAC Official Method 2000.12 (AOAC International, 2007), and although the method is standardized, variation exists both within and among laboratories (Gizzi et al., 2008). Because there are differences in the biochemical nature of phytases, however, modifications in the initially established laboratory analysis have become common (Kim and Lei, 2005; Selle and Ravindran, 2008). As a consequence, expression of phytase activity can vary depending upon phytase source and method of analysis (Jones et al., 2010b; Kerr et al., 2010).

Increases in total tract digestibility of P and reductions in P excretion from pigs is usually observed as phytase is added to diets fed to swine (Selle and Ravindran, 2008; Almeida and Stein, 2010). However, the magnitude of the response is affected by the ingredients in the diet (Düngelhoef et al., 1994; Johansen and Poulsen, 2003; Almeida and Stein, 2010), the amount and source of supplemental phytase (Selle and Ravindran, 2008; Jones et al., 2010b; Kerr et al., 2010), and the Ca:P ratio (Adeola et al., 1998; Selle et al., 2009; Letourneau-Montminy et al., 2010).

The effects of phytase on other components of the diet have been investigated in several experiments. In some experiments, positive effects on the digestibility of energy, amino acids, and minerals have been reported. In other experiments, no such effects have been observed, suggesting that any effects are quite variable and may depend on other dietary factors.

FEED FLAVORS

Flavors, sweeteners, aromas, or their combinations are feed additives that are used in an effort to improve palatability, initiate acceptance, or mask off-flavors when added to swine diets (Jacela et al., 2010a). There is strong evidence that pigs have a high preference for sweet tastes (Kennedy and Baldwin, 1972; Danilova et al., 1999; Glaser et al., 2000). Traditionally, sucrose is used in diets for young pigs both as a palatability enhancer and as an energy source. Alternatively, artificial high-intensity sweeteners such as saccharine, neohesperidin dihydrochalcone, and thaumatin are some of the more commonly used flavors. Among hundreds of flavors and flavor combinations, weanling pigs only had a significant preference for cheesy, fruity, meaty, or sweet flavors (McLaughlin et al., 1983).

Flavors added to lactation diets resulted in greater creep feed consumption when litters were exposed to specific flavors associated with the sow diet or the milk of the sow (Campbell, 1976; King, 1979; Langendijk et al., 2007). In suckling pigs, flavors may be added to the creep feed to initiate acceptance of solid food and to increase consumption and weaning weights; however, results were either variable (Gatel and Guion, 1990) or negligible (King, 1979; Millet et al., 2008; Sulabo et al., 2010). Flavors are most often applied to nursery pig diets to improve feed intake immediately postweaning. However, growth performance of newly weaned pigs was not affected by the presence of flavors in the diets (Munro et al., 2000; Sterk et al., 2008; Seabolt et al., 2010; Sulabo et al., 2010). In some experiments (Costa et al., 2003; Sulabo et al., 2010), flavors were added to noncomplex weanling pig diets, but pigs fed these diets did not obtain similar growth performance as pigs fed unflavored, complex diets. Experiments with growing and finishing pigs also failed to demonstrate any performance benefits from adding flavors to the diet (Koch et al., 1976, 1977; Johnston et al., 1989). Overall, these results indicate that feed intake and growth performance are mostly unaffected by the addition of flavors and sweeteners to the diet.

MYCOTOXIN BINDERS

Toxigenic molds and their associated mycotoxins are undesirable contaminants of feedstuffs and animal feeds. Mycotoxins, which are secondary metabolites produced by filamentous fungi such as *Aspergillus* spp., *Fusarium* spp., and *Penicillium* spp., elicit toxic responses (mycotoxicoses) when ingested by animals. The most relevant mycotoxins in diets fed to swine are aflatoxin B1, zearalenone, deoxynivalenol (DON), T-2 toxin, fumonisin B1, and ochratoxin A. The biochemical mode of action and clinical effects of these mycotoxins to animals has been reviewed (Newberne and Butler, 1969; Fink-Gremmels and Malekinejad, 2007; Glenn, 2007; Pestka, 2007; Voss et al., 2007). Though each may have specific effects, mycotoxins generally lead to economic losses due to feed refusal, poor feed conversion, reduced weight gains, immune suppression, interference with reproductive capacities, or production of residues in animal products. Additional information about mycotoxins is discussed in Chapter 11.

There are physical and chemical methods for preventing, decontaminating, or minimizing the toxicity of mycotoxins from preharvest, harvest, storage, and processing of plant ingredients used as animal feedstuffs (Samarajeewa et al., 1990; Jouany, 2007). Biological methods to inactivate mycotoxins may also be used. This involves the use of nonnutritive agents called mycotoxin binders that are added to animal feeds to inhibit or reduce the absorption or promote the excretion of mycotoxins in the feed. This is accomplished mostly through deactivation of mycotoxins by binding to adsorbents, but some mycotoxin inhibitors detoxify the mycotoxins and produce less toxic metabolites.

Reviews on the use of adsorbents against mycotoxicoses have been published (Ramos et al., 1996; Ramos and Hernandez, 1997; Huwig et al., 2001; Avantaggiato et al., 2005; Diaz and Smith, 2005). Inorganic binders include silicate clays, activated carbon, and polyvinyl polypyrrolidine (PVPP). Clays are silicate minerals that include natural (clinoptilolite) or synthetic (zeolite A) zeolites, bentonites, and hydrated sodium calcium aluminosilicates (HSCAS). There is limited research on zeolites as mycotoxin binders in swine, but results of experiments with broilers indicate that dietary zeolites may reduce the negative effects of aflatoxicoses (Miazzo et al., 2000; Oğuz and Kurtoglu, 2000; Oğuz et al., 2000a,b; Piva et al., 2005). Bentonites, which have good ion exchange capabilities, are classified as calcium, magnesium, potassium, or sodium bentonites, and they are effective against aflatoxicoses in pigs (Schell et al., 1993a,b; Miazzo et al., 2005). Hydrated sodium calcium aluminosilicates are the most studied adsorbents against mycotoxins. Phillips et al. (1988) first demonstrated the high affinity and capacity of HSCAS to bind aflatoxin B1 in broilers. Aflatoxin reacts at multiple sites on HSCAS clay particles and binds to highly negative surfaces via chemisorption (Grant and Phillips, 1998). Research on the effects of HSCAS on aflatoxicoses has been reviewed (Ramos and Hernández, 1997; Phillips, 1999; Bingham et al., 2003). Generally, HSCAS has high efficacy in ameliorating the effects of aflatoxin in pigs (Colvin et al., 1989; Beaver et al., 1990; Lindemann et al., 1993; Schell et al., 1993b; Harvey et al., 1994). However, the use of silicate clays in swine diets contaminated with other mycotoxins failed to minimize the effects of mycotoxicoses (Patterson and Young, 1993; Williams et al., 1994; Doll et al., 2005).

Activated carbon (or charcoal) is an amorphous form of carbon heated in the absence of air and treated with oxygen to open millions of pores between carbon atoms (Diaz and Smith, 2005). It is a highly absorbent powder commonly used as medical treatment for severe intoxications (Huwig et al., 2001). However, adding activated charcoal to diets fed to pigs and broilers contaminated with aflatoxin B1 or other mycotoxins failed to improve growth performance, relative organ weights, or immune function (Dalvi and Ademoyero, 1984; Edrington et al., 1997; Cabassi et al., 2005; Piva et al., 2005).

Polyvinyl polypyrrolidine (PVPP) is a chemically inert substance composed of cross-linked polymers of polyvinyl pyrrolidine, which is insoluble in water and has high adsorbing capacity. It forms a hydration hull around its particles and attracts polar molecules, such as aflatoxin (Çelik et al., 2000). There is some research to evaluate the efficacy of PVPP against mycotoxicoses in poultry (Kececi et al., 1998; Kiran et al., 1998; Çelik et al., 2000), but very limited work has been completed in swine. Friend et al. (1984) demonstrated that PVPP did not alleviate the toxicity of DON in pigs.

Glucomannan polymers derived from yeast cell walls are also used as organic adsorbents. Although their specific mode of action is not fully elucidated, in vitro work indicates that β-D-glucans may be the main component that adsorbs mycotoxins (Yiannikouris et al., 2006). However, adding 0.2% glucomannan polymers to diets naturally contaminated with a mixture of *Fusarium* mycotoxins did not alleviate the negative effects of mycotoxicoses in weanling pigs (Swamy et al., 2002, 2003), gestating gilts, or lactating sows (Díaz-Llano and Smith, 2006, 2007; Díaz-Llano et al., 2010). Recently, the use of microorganisms such as *Eubacterium* BBSH 797 and *Trichosporon mycotoxinovorans* was shown to have the capability to deactivate ochratoxin A and zearalenone via enzymatic degradation prior to their resorption in the gastrointestinal tract (Schatzmayr et al., 2006). However, in vivo experiments with pigs demonstrating the efficacy of *Eubacterium* BBSH have not been published.

Despite the significant research on different mycotoxin binders, there are no products that have been approved by the FDA for the prevention or treatment of mycotoxicoses. Silicate clays have GRAS status, but are only authorized for use as anticaking agents and pellet binders in animal feed (AAFCO, 2010).

ANTIOXIDANTS

Antioxidants are added to feed or to feed ingredients to inhibit oxidation of fat and vitamins because oxidation may produce off-flavors, cause rancidity, and destroy fat-soluble vitamins (Jacela et al., 2010a). Vitamin E, vitamin C, and Se are effective antioxidants that help reduce the susceptibility of animal tissue to lipid oxidation (Mahan et al., 1994, 1996; Lauridsen et al., 1999). However, if it is assumed that these nutrients do not provide sufficient antioxidative status to the feed or to ingredients, nonnutritive antioxidants may be used. Sometimes a combination of several commercial products is used (Jacela et al., 2010a). Typically used commercial antioxidants include ethoxyquin, butylated hydroxytoluene (BHT), butylated hydroxyanisole (BHA), and propyl gallate (Jacela et al., 2010a).

Addition of commercial antioxidants is recommended if diets or feed ingredients that contain unsaturated fatty acids (i.e., fish meal, distillers dried grains with solubles, and corn coproducts) are stored under hot conditions. These diets and ingredients are susceptible to rapid oxidation, but oxidation can be delayed by addition of antioxidants.

PELLET BINDERS

Pelleting of diets may improve growth performance of weanling and growing-finishing pigs compared with pigs fed diets in a meal form (Hansen et al., 1992; Traylor et al., 1996; Potter et al., 2010). However, effects of feeding pelleted diets depend on the physical quality of the pellets (Stark et al., 1994). Pellet binders are feed additives used to improve pellet durability and reduce the amount of feed fines that are incurred during feed manufacturing, packaging, and transport. These binders attempt to improve adhesion and cohesion between feed particles (Thomas and van der Poel, 1996), which require water to activate the binding agent. Though pellet binders can improve pellet quality, ingredient composition of the diet and feed-processing technology also play important roles in determining the quality of pellets of a specific diet (Thomas and van der Poel, 1996).

The most common pellet binders used in animal feed production are inorganic clays such as bentonite, sepiolite, montmorillonite, lignosulphonates, collagen protein derivatives such as gelatin, and cellulose gums. Inorganic clays are used as pelleting aids that act as fillers to decrease porosity of the pelleted feed and as a lubricant (Thomas et al., 1998). Clays improve pellet durability, especially when diets are high in fat (Salmon, 1985; Angulo et al., 1995). However, to obtain a positive response, these pellet binders often need to be included at relatively high inclusion rates (2-3% of the diet). Water-soluble lignosulphonates are byproducts from the paper industry that increase pellet durability and decrease energy consumption (Van Zuilichem et al., 1979a,b, 1980). Recommended inclusion rates for lignosulphonates are between 0.5 and 3% (Thomas et al., 1998). The maximum recommended inclusion of inorganic clays and lignosulphonates are 2 and 4% of finished feed, respectively (AAFCO, 2010).

FLOW AGENTS

Flow conditioners and anticaking agents are used as additives to prevent caking and improve the flowability of granular or powdered ingredients and meal diets during handling, storing, and processing. Flow agents are usually made from chemically inert, water-insoluble substances that possess a high ability to adsorb moisture as a result of their very large surface areas (Ganesan et al., 2008b). Inorganic clays used as pelleting aids are also the most commonly used flow agents, and they may be included by up to 2% of the diet (AAFCO, 2010). Though research has been conducted to investigate effect of flow agents on flow properties of granular solids and powders (Chen and Chou, 1993; Onwulata et al., 1996; Jaya and Das, 2004), very limited data have been published on the use of flow agents in ingredients commonly used in the feed industry. However, results of recent experiments indicated that the flowability of distillers dried grains with solubles is not improved by the use of flow agents (Ganesan et al., 2008a; Johnston et al., 2009).

RACTOPAMINE

Ractopamine or ractopamine hydrochloride belongs to a class of compounds considered β-adrenergic receptor agonists. The only ractopamine product that is approved for use in the United States is marketed by Elanco Animal Health under the name Paylean®. The mechanisms of ractopamine action have been reviewed (Mills, 2002) and effects of ractopamine on changing the body composition of pigs are well documented (Watkins et al., 1990; Dunshea et al., 1993; See et al., 2004). Dietary ractopamine results in reduced lipid accretion and increased carcass lean percentage (Mitchell et al., 1991; Moody et al., 2000); however, results of some experiments have indicated inconsistent or no effects of ractopamine on lipid deposition (Dunshea et al., 1993). The inconsistent effects of ractopamine on fat accretion have been explained by a downregulation of the β-adrenergic receptors in adipose cells, which occurs after prolonged administration of ractopamine (Spurlock et al., 1994).

Effects of ractopamine administration on nutrient requirements of pigs have been reviewed (NRC, 1994). Ractopamine administration increases growth performance, carcass lean indicators, and weights of the gastrointestinal tract, liver, and kidneys, but whole-animal heat production is not affected (Yen et al., 1991). The underlying mechanisms related to β-agonist administration may be related to the fact that energy expenditure is increased and nutrients are redirected away from lipid deposition and toward lean deposition, which may explain whole-animal changes in carcass composition of pigs fed ractopamine-containing diets (Reeds and Mersmann, 1991). Because of the increased lean deposition, pigs fed ractopamine have greater needs for dietary indispensable amino acids (AA) than pigs fed diets without ractopamine, and greater AA:metabolizable energy (ME) ratios are, therefore, needed in diets containing ractopamine (Schinckel et al., 2003; Apple et al., 2004).

In the United States, ractopamine is approved for inclusion in diets for growing-finishing pigs (> 68 kg) for the last 23-41 kg of BW gain. Inclusion is approved at concentrations of 5-10 ppm (5-10 g per 1,000 kg of complete diet). In addition, label guidelines state that diets containing ractopamine have to contain at least 16% CP.

The pig growth model (Chapter 8) simulates the response to ractopamine during the late-finishing period and predicts energy and nutrient requirements. Utilizing a three-phase step-up ractopamine supplementation program (95-120 kg) for gilts, the predicted requirement for standardized ileal digestible (SID) lysine is 19 g/day for ractopamine-fed animals at 120 kg with an average lean gain of 350 g/day. The requirement for SID lysine of 120-kg gilts fed a diet containing no ractopamine is only 15 g/day, so addition of ractopamine increased the requirement for SID lysine by 26%. Likewise, the predicted daily requirement for phosphorus increased approximately by 29%, whereas the predicted ME intake decreased by 3% in pigs fed ractopamine compared with pigs fed no ractopamine.

CARNITINE AND CONJUGATED LINOLEIC ACIDS

Effects of adding carnitine and conjugated linoleic acids to diets fed to pigs are discussed in Chapter 3.

ODOR AND AMMONIA CONTROL COMPOUNDS

Effects of adding odor and ammonia control compounds to diets fed to pigs are discussed in Chapter 14.

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11

Feed Contaminants

INTRODUCTION

In addition to nonnutritive feed additives that may be specifically added to a diet for purposes other than nutrition (Chapter 10), many diets may contain items that are either innocuous or that could be harmful to pigs or other animals. These items, even those considered innocuous, are classified as contaminants. Contaminants may be grouped into three categories: chemical, biological, and physical. Natural contamination of feed occurs routinely and, while efforts to minimize contaminations have to be practiced, it is often of little concern. However, because of adverse occurrences in animal health caused by deliberate adulteration of the feed/food supply (e.g., melamine; Sharma and Paradakar, 2010) and because of times of extreme natural contamination of the feed/food supply (e.g., mycotoxins; Pollock, 2010) during some harvest seasons, contaminants are becoming issues to be monitored with increasing scrutiny.

This chapter, presented for the first time in the NRC Nutrient Requirements of Animals series, is added not because of any known or perceived problems specific to the feed supply for swine but simply because feed contaminants of a variety of sorts can affect animal health and well-being and have been demonstrated to do so, albeit infrequently, in a variety of species in a variety of locales. Because of the international nature of commerce related to feedstuffs as well as products from domestic animal production, the safety of the feed/food supply system is a matter of worldwide importance. The provision of a safe feed supply has long been a priority for feed manufacturers in many countries and has been led by the efforts of a variety of organizations, including governmental organizations such as the U.S. Food and Drug Administration (FDA) and U.S. Departmentof Agriculture (USDA) Animal and Plant Health Inspection Service as well as industry organizations such as the Association of American Feed Control Officials and the American Feed Industry Association. The purpose of this chapter is to help maintain and enhance those efforts aimed to assure the public of a safe feed/food supply through the summarization of some of the current issues, efforts, and research involving a variety of domestic animal species throughout the world.

CHEMICAL CONTAMINANTS

Chemical contamination is generally considered to be of greater concern than either biological or physical contamination. There are three primary subcategories of chemical contaminants: pesticides and pesticide residues, mycotoxins, and heavy metals/radionuclides. Pesticides (and pesticide residues) are numerous; those listed in the draft list of potentially hazardous contaminants in the FDA Animal Feed Safety System (FDA, 2011) include aldrin, benzene hexachloride, chlordane, chlorpyrifos, chlorpyrifos-methyl, diazinon, dieldrin, dichlorodiphenyltrichloroethane + tetrachlorodiphenylethane + dichlorodiphenyldichloroethylene (DDT + TDE + DDE), dicofol, endosulfan, endrin, ethion, α-hexachlorocyclohexane (HCH), β-HCH, γ-HCH (lindane), heptachlor, heptachlor + heptachlor epoxide, hexachlorobenzene, malathion, methoxychlor, mirex, parathion, toxaphene (camphechlor), and tribuphos. Some of these compounds are currently in agricultural use, whereas others have been banned from use for various periods of time but persist in the environment. The mycotoxins listed in the FDA (2011) document are the aflatoxins (B_1, B_2, G_1, and G_2), fumonisins (B_1, B_2, and B_3), deoxynivalenol (DON or vomitoxin), ochratoxin, and zearalenone. The heavy metals/radionuclides listed are arsenic, cadmium, chromium, lead, ^{241}americium, ^{134}cesium, ^{131}iodine, ^{238}plutonium, ^{103}ruthenium, ^{106}ruthenium, and ^{90}strontium. Radionuclides are not a contaminant of primary concern for swine feeds, but D'Mello (2000) pointed out that after the Chernobyl accident in 1986, ^{134}caesium and ^{137}caesium were released, causing widespread contamination of pastures and stored forages. As a consequence, milk and sheep carcasses became contaminated and restrictions were imposed on the movement and slaughter of sheep. In addition to these three primary subcategories, other chemicals such as ethoxyquin, dioxins, mercury, perchlorate, polychlorinated biphenyls (PCBs), polyethylene glycol, and selenium are listed.

Pesticides

A variety of chemicals such as herbicides, fungicides, and pre- and postharvest insecticides are used in grain production. Van Barneveld (1999) reviewed the effects of many of these in Australian grains that were subsequently used in livestock feeds. Studies in laying hens demonstrated that combining certain insecticides at levels that separately had no effect decreased bird performance and efficiency. Feeding barley treated with glyphosate and/or ethephon to pigs gave mixed results, with some studies demonstrating no adverse effects and other studies demonstrating reduced survival rate in pigs born to sows receiving certain treatments. The results vary but indicate that herbicide/pesticide residues in feed may cause adverse effects in some situations. In addition, combinations of products/residues that may occur in crop production that do not occur in the preclearance regulatory approval process may result in adverse animal responses not identified in the approval process.

From 1989 to 1994, the FDA collected > 500 samples of mixed livestock feed and analyzed for organohalogen and organophosphorus pesticides (Lovell et al., 1996). Only 16.1% contained no detectable pesticide residues. In the samples with detectable pesticide levels, 804 residues (654 quantifiable and 150 trace) were found, but none exceeded regulatory limits. The most commonly detected pesticides were five organophosphorus compounds (malathion, chlorpyrifos-methyl, diazinon, chlorpyrifos, and pirimiphos-methyl) that accounted for 93.4% of all pesticide residues detected. The most commonly detected organohalogen compounds were methoxychlor, DDE, polychlorinated biphenyls (PCB), dieldrin, pentachloronitrobenzene, and lindane, but these six compounds combined accounted for only 4.1% of residues detected.

The persistence of some banned products is illustrated by the organochlorine pesticides that still appear as residues in livestock products. Because they are lipoid compounds, they bioconcentrate in the food chain and are accumulated in the fat. This persistence is demonstrated by the findings of Furusawa and Morita (2000), who, in 1998, measured the contaminating and accumulating levels of organochlorine pesticides in extractable fats from a basal diet, eggs and seven tissues (adipose tissue, blood, kidney, liver, muscle, ovary, and oviduct), and excreta of laying hens that were kept in a general poultry farm in Japan. Organochlorine pesticides were discontinued for use in Japanese agriculture around 1970, but dieldrin and all forms of DDT investigated were still present in the dietary fats. Furthermore, dieldrin and certain forms of DDT were found in all the tissue fats and egg yolk fats but were not detected in the dried excreta. Although the persistence was evident for all organochlorine pesticides detected, the accumulated levels were well below the practical residue limits.

Mycotoxins

Mycotoxins are secondary metabolites of filamentous fungi (molds) that, when ingested by animals, can cause a variety of adverse physiological responses. Some typical effects are feed refusal, digestive problems, nervous system problems such as tremors and weakness, reproductive problems from reduced conception rates to abortion, immune suppression, organ damage, and cancer. Although hundreds of mycotoxins have been identified, the primary ones that cause problems in pigs are the aflatoxins (B_1, B_2, G_1, and G_2), zearalenone, deoxynivalenol (DON or vomitoxin), the fumonisins, and ochratoxin A. These five toxins are produced by various *Aspergillus* spp. (aflatoxins and ochratoxin), *Fusarium* spp. (zearalenone, DON, and fumonisin B_1) or *Penicillium* spp. (ochratoxin). The fungi are both field fungi and storage fungi. Growth of the fungi is largely dependent on environmental conditions, especially temperature and humidity during critical periods of plant growth or feedstuff storage. Although each toxin may elicit several nonspecific responses, each is known to have a primary response. The aflatoxins are potent hepatotoxins, zearalenone has hyperestrogenic effects, DON affects feed intake and the gastrointestinal tract, fumonisin B_1 causes pulmonary edema in swine, and ochratoxin is a nephrotoxin.

Placinta et al. (1998) presented a review of worldwide contamination of cereal grains and animal feed with *Fusarium* mycotoxins. The review demonstrates ubiquitous presence, but also definite regionality, with regard to concentrations of the various toxins. A commercial survey (BIOMIN, 2010) also revealed the broad presence of mycotoxins not only in terms of world regions but also in terms of commodities. The survey involved 9,030 analyses on 2,660 samples. Analyses were for aflatoxins, zearalenone, DON, fumonisins, and ochratoxin A on a wide variety of feedstuffs (e.g., cereals, byproduct feeds, and finished feed). As in surveys from previous years conducted by the company, corn was the most extensively and highly contaminated commodity; 75% of the samples were contaminated with at least one mycotoxin and 40% were contaminated with more than one mycotoxin. In addition to the presence of mycotoxins in cereals, mycotoxins can be concentrated in byproducts from those cereals such as distillers dried grains with solubles (DDGS) or condensed distillers solubles (CDS). Schaafsma et al. (2009) determined that DON concentrations in the CDS and the final DDGS coproduct were higher than in the starting material (corn grain). Toxin concentration increased by a factor of three on a dry weight basis in DDGS compared with the starting corn and by a factor of four in CDS.

The FDA has issued regulatory guidance for two toxins and contaminants that may be present in raw grains and finished feed: aflatoxin and DON. The FDA issues policy guidance or enforcement pronouncements in one of three forms: "advisory levels" to provide guidance to the industry concerning levels of a substance present in food or feed that are believed by the agency to provide an adequate margin of safety to protect human and animal health, "action levels" when it wishes to specify a precise level of contamination at which the agency is prepared to take regulatory action, and "regulatory limits" for the presence of toxins or contaminants that have been established after issuing valid regulations under the public notice-and-comment rulemaking procedures set forth in the Administrative Procedure Act. A summary of the FDA Regulatory Guidance for Toxins and Contaminants can be found at the National Grain and Feed Association website[1] and more detailed background information or updated information is available in FDA guidance documents (2000, 2001, and 2010b).

More complete information about the occurrence of mycotoxins, their effects in different species or specific effects in pigs, and possible means of dealing with contaminated feedstuffs is available in NRC (1979), CAST (1989, 2003), and Kanora and Maes (2009). For countries other than the United States, information about mycotoxins (primarily) and other contaminants or action levels can be viewed at the FAO website.[2]

Heavy Metals

Minerals used in swine feeds can be mined or reclaimed by recycling manufactured materials. Depending on the mineral source and methods of purification or extraction, various elements that are not of primary interest may be retained in the finished product. Similarly, when minerals used in animal agriculture are obtained from recycled materials, the procedures used will affect the potential presence of undesirable minerals/metals. The byproduct streams from these industrial processes and the manner in which they are handled have the potential to affect animal agriculture through airborne particulate distribution or through such means as the application of that byproduct as a fertilizer for crop needs of nitrogen, phosphorus, and potassium.

In two studies with dairy cows, Vreman et al. (1986) evaluated the transfer of cadmium, lead, mercury, and arsenic from feed into milk and various tissues after the cows were fed the metals directly or via harbor sludge or sewage sludge. In the first study, administration of the heavy metals directly was at levels that were 4 to 75 times the control intake for a period of 3 months. The second study utilizing sludge was conducted for 28 months. At the end of the feeding period, examination of tissues revealed that liver and kidney were the primary sites of accumulation of the metals; there was also a dose-related increase in bone lead. However, the increased intake of heavy metals did not result in significantly higher concentrations of these elements in milk, blood, or muscle. An industry survey related to the contamination of mineral premixes and complete feeds with heavy metals in the Asia-Pacific region was reported by Timmons (2010). Samples were analyzed to determine the proportion that would exceed the European Union (EU) established standards for undesirable substances by Directive 2002/32/EC,[3] which gives maximum limits for undesirable substances in feed additives relative to arsenic (15 ppm), cadmium (10 ppm), lead (100 ppm), and mercury (0.05 ppm). With regard to the percentage of samples contaminated by at least one heavy metal over the EU limit, samples from the 10 countries surveyed ranged from 3 to 43% of the samples being considered contaminated. Of 25 poultry premixes that were sampled, 48% were found to be contaminated with at least one heavy metal over the EU limit; of 30 complete feeds containing supplemental inorganic minerals, 7% were found contaminated with at least one heavy metal. A survey in the United States (Kerr et al., 2008) identified specific mineral sources that would exceed the EU level for lead. Guidelines for contaminant levels permitted in mineral feed ingredients in the United States are provided by AAFCO (2010).

Apart from the use of sewage sludge as a crop fertilizer or the unwitting use of contaminated mineral premixes, the most likely source of heavy metal contamination is the use of fish meals that may contain mercury. Mercury is well known to accumulate in fish and the use of fish meals containing mercury can result in its accumulation in products from livestock. The mercury content of fish meals varies depending on the type of fish used for the fish meal and in the waters from which it was obtained (Johnston and Savage, 1991). Early work with the direct supplementation of mercury to pigs (Chang et al., 1977) and the use of fish meal for pigs and poultry (Stothers et al., 1971) established a relationship between dosage and form of mercury to tissue levels. Both studies also demonstrated that the greatest accumulation was in hair, kidney, and liver. Stothers et al. (1971) demonstrated a species difference with poultry accumulating less mercury in relation to dietary levels than pigs. A review of the potential of the use of fish meal in a variety of livestock species and its effect on human health was presented by Dórea (2006).

Lin et al. (2004) observed that the addition of 0.3% montmorillonite clay nanocomposite to the diet markedly decreased ($P < 0.05$) mercury levels of blood, muscle, kidney, and liver tissue, demonstrating that the addition of this nonnutritive adsorptive material effectively reduced the gastrointestinal absorption of mercury via its specific adsorption. Thus, the potential toxicity of any heavy metal may be a function of not only its concentration in the finished feed, but also the presence of other feed components with which it may interact.

[1]http://www.ngfa.org/files/misc/Guidance_for_Toxins.pdf (Accessed May 10, 2011.)

[2]http://www.fao.org/docrep/007/y5499e/y5499e00.htm or http://www.fao.org/docrep/W8901E/W8901E00.htm. (Accessed May 10, 2011.)

[3]http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2002L0032:20061020:EN:PDF (Accessed on May 11, 2011.)

Other Chemical Contaminants

Melamine—cyanurotriamide ($C_3H_6N_6$; MW126.12; Merck Index, 2006)—is a compound of high N content (66.64%). Whenever the crude protein content of a food/feed is calculated by the measurement of its N content multiplied by the 6.25 factor, a small amount of melamine can give the adulterated product an appearance of a much higher crude protein content because melamine itself appears to have a crude protein content of 416.5% (66.64% N × 6.25). As mentioned in the introduction, grain byproducts and powdered milk in China were intentionally adulterated with melamine to elevate the perceived crude protein content. An account of this occurrence and the industrial uses of melamine were summarized by Sharma and Paradakar (2010). In brief, pet food in North America was determined to have been adulterated with melamine in 2007, and, in 2008, melamine was discovered to have been systematically added to powdered milk for infants, resulting in about 300,000 children being sickened and at least six dying in China.

Polychlorinated biphenyls (PCBs) and dioxins (a collective term for polychlorinated dibenzofurans and polychlorinated dibenzo-*p*-dioxins) are highly toxic entities and of much concern. They are rapidly absorbed from the gastrointestinal tract and can elicit pathological effects in the gastrointestinal tract and nervous and reproductive systems. The PCBs and dioxins have immunosuppressive effects and there is evidence of transplacental transport and fetal accumulation as well as accumulation in breast milk (Calamari, 2002). The basis for the wide industrial use of PCBs lies in their physical and chemical properties as they are fire resistant; have a very low electrical conductivity; offer high thermal conductivity; have extremely high resistance to chemical breakdown; and, under normal environmental conditions, are chemically very stable. Dioxins are generated as contaminants in the preparation of a number of products containing chlorine (industrial chemicals and pesticides) or by burning materials containing chlorinated substances, particularly if the oxygen supply is limited and the incineration temperature is not high enough. An excellent review of this subject was provided by Calamari (2002). Dioxins can subsequently enter the feed/food supply chain through contaminated fats (Feed Info News Service, 2010b) or contaminated premixes (Feed Info News Service, 2010c) and, when present above acceptable levels, can cause massive feed recalls and disruptions of the feed and animal production industry (Feed Info News Service, 2009, 2011c,d; Feedstuffs, 2011).

Regulatory control of contaminants has been demonstrated to benefit the human food supply. Schwind and Jira (2008) investigated the levels of dioxins and PCBs in German meats and meat products and observed that all investigated types of meat were significantly below the maximum residue levels in the EU. Compared to a similar study in Germany about 10 years previously, the dioxin contents, especially in poultry and beef, had decreased significantly.

BIOLOGICAL CONTAMINANTS

There are two primary subcategories of biological contaminants: the transmissible spongiform encephalopathies (TSE) and bacteria. Within TSE, two are of primary interest in the United States relative to animals: bovine spongiform encephalopathy (BSE) and chronic wasting disease (CWD). The bacteria of concern relative to potential feed contamination for livestock are the *Bacillus* spp., *Clostridium* spp., *Escherichia coli*, *Mycobacterium* spp., *Pseudomonas* spp., *Salmonella enterica* (various serotypes), and *Staphylococcus* spp., but not all are of primary importance to swine.

Transmissible spongiform encephalopathies are a family of diseases affecting humans and animals that are characterized by a degeneration of brain tissue, giving it a sponge-like appearance, which could lead to death. The TSE include BSE in cattle, scrapie in small ruminants (such as sheep and goats), and CWD in cervids (such as deer and elk). The TSE are largely attributed to a particle, known as a prion, which is an infectious agent composed primarily of an abnormal form of protein. First diagnosed in the United Kingdom in 1986, BSE turned into an epidemic because meat and bone meal produced from infected animal carcasses was included in animal feed. Much of the history of the observation of the developing problem and the discovery of its etiology was detailed in an FAO (1998) publication. Because standard rendering processes do not completely inactivate or kill the BSE agent, rendered protein such as meat and bone meal derived from infected animals may contain the infectious agent. As stated in a BSE bulletin (USDA, 2006), the USDA Animal and Plant Health Inspection Service (APHIS), in cooperation with the FDA and the USDA Food Safety and Inspection Service (FSIS), has taken aggressive measures to prevent the introduction and potential spread of BSE in the United States. Although BSE has been identified in cattle imported into the United States from Canada, APHIS has maintained stringent restrictions since 1989 to prevent importation of the highest risk animals and products. In 1997, the FDA implemented regulations that prohibit the feeding of most mammalian proteins to ruminants, including cattle. Both the stringent oversight of imported cattle and the feed ban are important measures to prevent the transmission of disease to cattle. Although this is an important area of concern for the feed industry, it is not currently an issue of concern for the swine industry.

Bacterial contamination of feed is an area of much debate because it is not universally agreed that feed is a primary means whereby bacterial contamination of the human food supply occurs. As noted by D'Mello (2000), there is considerable interest in the occurrence of *E. coli* in animal feeds following the association of the O157:H7 serotype of these bacteria with human illness. Certainly much of the potential contamination of meat is related to practices during slaughter and practices in the retail and home environment. However, although a survey by Lynn et al. (1998) found that none of the 209 cattle feeds sampled from commercial sources and farms was positive for *E. coli* O157:H7, the fact that 30% were positive for generic *E. coli*, coupled with the fact that follow-up experiments demonstrated that mixed rations were able to support the replication of *E. coli*, demonstrates that feed may contribute to *E. coli* in animal agriculture. The ability of the experimental rations to support the replication of *E. coli* was correlated with the concentration of organic acids in the corn silage that was used in the ration, suggesting that the ability of any feed to support replication of any bacteria will be a function of the particular food supply and conditions for growth needed by the particular bacterial strain.

Molla et al. (2010) determined the occurrence and genotypic relatedness of *Salmonella enterica* isolates recovered from feed and fecal samples in commercial swine production units. The occurrence of genotypically related and, in some cases, clonal strains, including multidrug-resistant isolates in commercially processed feed and fecal samples, suggests the high significance of commercial feed as a potential vehicle of *Salmonella* transmission. Wales et al. (2010) reviewed a variety of data to describe the various modes of action and efficacies of different chemical agents delivered in feed or in drinking water against *Salmonella* occurring in feed or in the livestock environments. The review illustrated that the efficacy of the decontamination of feed and feed ingredients using chemical agents has to take into account the likelihood of initial contamination rates, opportunities for recontamination in storage and transfer, and the susceptibility of the target livestock to *Salmonella* infection. The FDA (2010a) recently solicited input from interested parties about a draft compliance policy guide that has been developed relative to *Salmonella* in animal feed. Comments were requested on its proposal that certain criteria be considered in recommending enforcement action against animal feed or feed ingredients that are adulterated because of the presence of *Salmonella*. When finalized, the document will guide FDA's regulatory policy relating to animal feed or feed ingredients that are contaminated with *Salmonella* and that come in direct contact with humans, such as pet food and pet treats. The draft policy guide focuses on selected serotypes based on their potential impact on human health rather than a complete ban; thus, not all incidents of *Salmonella* being found in feed will be occasion to deem the feed adulterated.

PHYSICAL CONTAMINANTS

Physical contaminants of plastic, glass, and metal can occasionally be found in finished feeds. Much of this potential contamination can be controlled through proper cleaning and sanitation in the feedmill. Metals in the grain stream can be collected by properly located magnets in the equipment through which the grain passes before processing. Other contamination, such as vermin carcasses, is also a function of sanitation and proper attention to limitation of access of the feedmill by vermin. Guidelines for sanitation and pest management are provided by Pedersen (1985).

POTENTIAL FUTURE ISSUES

In the United States and many other countries, genetically modified (GM) crops are widely grown and fed to pigs. However, some countries do not permit feedstuffs developed by those technologies, and, for the purposes of international trade, they are considered "contaminants." Recently, the European Commission's Standing Committee on the Feed Chain and Food Safety approved Regulation EC 619/2011 to allow up to 0.1% of GM material in animal feed imports (Europa, 2011). The establishment of an actual level that would not be deemed adulterated has been well received by the feed industry. (Feed Info News Service, 2011a). Because future analytical improvements may be able to find levels that are not currently detectable, setting the level of "contamination" at zero may cause extreme difficulties in moving bulk-handled products through common traffic areas because minute spillage can contaminate many other products moving through that same area.

Lynas et al. (1998) surveyed more than 400 feedstuffs and premixes for possible contamination with antimicrobial agents (40% of the samples were supposed to be free of medication, whereas 60% had a medication claim). Of the medicated feeds, 35% contained undeclared antimicrobials and of the unmedicated feeds, 44% were shown to contain detectable levels of antimicrobials. The most frequently identified contaminating antimicrobials were chlortetracycline (15.2%), sulphonamides (6.9%), penicillin (3.4%), and ionophores (3.4%). All the contaminating concentrations of sulphadimidine detected were sufficient to cause violative tissue residues if fed to animals immediately before slaughter. The issues observed by Lynas et al. (1998) were probably related to feedmill management relative to diet sequencing, mixer cleanout between batches, or inadequate employee understanding. However, another potential situation wherein contamination can occur in an international economy is illustrated by the discovery of chloramphenicol (a broad-spectrum antibiotic that is banned in some but not all countries) residues in vitamin premix (Feed Info News Service, 2011b).

Because antibiotics are used in many industrial processes, their residue in byproducts resulting from those processes is a potential issue. In the United States, the FDA conducted a nationwide survey of distillers dried grains (DDG) for antibiotic residues to track and test the residues of antibiotics such as virginiamcyin, penicillin, and erythromycin, all of which may be used to control bacterial growth in fermentation tanks (FDA, 2009a). The survey examined 60 DDG samples, 40 from domestic sources and 20 from foreign sources. Because the extent to which this may even be a potential issue would depend on the manufacturing processes at each ethanol plant, the potential for these possible residues would be plant-specific as a report in 2009 from the Institute for Agriculture and Trade Policy indicated that almost 45% of U.S. ethanol production facilities are using options other than antibiotics to control bacteria in fermentation tanks (Geiver, 2010).

ANIMAL FEED SAFETY SYSTEM

The FDA announced in 2003 its intention to make its animal feed safety program more risk based and comprehensive. When completed, the modernized Animal Feed Safety System (AFSS) is intended to incorporate risk-based, preventive control measures for ensuring the safety of animal feed. The FDA, with assistance from the states, has developed an AFSS framework document that identifies the current major processes, guidance, regulations, and policy documents that address feed safety and the documents needed to make the agency's feed safety program comprehensive and risk based (FDA, 2011). An integral part of this effort is the development of a relative-risk ranking method for all potentially toxic or deleterious biological, chemical, and physical hazards in animal feed (FDA, 2009b). It is important to note that this risk-ranking exercise is not intended for the estimation of risks associated with any one feed contaminant; instead, it is intended to be a tool for ranking of the relative risks of feed contaminants to aid FDA in setting priorities for allocating its resources in a risk-based manner, an approach that is explained in more detail in FDA (2009b). A specific example involving swine is provided by FDA (2009c).

OTHER SOURCES OF INFORMATION

Ultimately, feed safety involves attention to a wide variety of details: sourcing of ingredients and quality checks related to those ingredients, proper storage of ingredients and finished feeds, feedmill sanitation and records, and appropriate regulation. The U.S. feed industry has done an excellent job of providing safe feed to the swine industry. Companies desiring to further enhance their quality control programs can obtain guidance from several areas. Information is provided in AAFCO (2010) about model feed safety program development guides. The Feed Additive Compendium (Lundeen, 2010), which is updated yearly by the Miller Publishing Company, has several excellent sections on current Good Manufacturing Practices that can assist in developing or maintaining a feed safety program.

An excellent proactive food safety leadership program, Safe Feed/Safe Food Certification Program, is available through the American Feed Industry Association (AFIA, 2009). The program is well developed with regard to the certifying inspections of participating organizations, record-keeping responsibilities, instructions or advice about ingredient purchases, identification and traceability of finished products, and issues related to many of the contaminants presented in this chapter.

In addition to the attention provided to feed manufacturing to control contamination and, thereby, assure good animal health and, ultimately, safe human food, attention directed toward potential water contaminants is also warranted. Issues related to water quality, contaminants, and pig health are reviewed in Chapter 5.

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12

Feed Processing

INTRODUCTION

Plant carbohydrates are typically classified into (1) simple sugars and their conjugates (e.g., glucose and fructose), (2) storage reserve compounds (e.g., starch), and (3) structural carbohydrates (e.g., cellulose and hemicellulose). This classification is described in more detail in Chapter 4. Simple sugars are typically easily digested in the upper gastrointestinal tract, and, therefore, are not likely to have their digestibility improved by feed processing. Starch is also primarily digested in the upper gastrointestinal tract (Svihus et al., 2005; Bach Knudsen et al., 2006; Wiseman, 2006), but depending upon the amylase:amylopectin ratio, native size of starch granule, and presence of α-amylase inhibitors, processing may increase its digestibility. Structural carbohydrates are complex and variable polysaccharides (Theander et al., 1989; Selvendran and Robertson, 1990; Bach Knudsen, 2001) that are not completely broken down by mammalian enzymes, and their digestibility may be improved by various processing techniques. Consequently, it would be advantageous to develop technologies to increase digestibility of energy and other nutrients in feedstuffs fed to swine in an effort to minimize the cost associated with providing digestible energy, minerals, and amino acids to growing animals. Feed processing (e.g., extrusion and expander processing, gelatinization, grinding or micronization, hydrothermal treatment, or pelleting) is one of these technologies that offer promise for improving the nutritional value of diets fed to swine.

EFFECTS OF PROCESSING ON NUTRIENT UTILIZATION

Processing of ingredients or diets may increase nutrient digestibility and, consequently, improve pig performance (Hancock and Behnke, 2001; Lundbald, 2009). Grinding effectively increases the surface area of the diet allowing increased access by digestive enzymes. Data reported by Ohh et al. (1983), Healy et al. (1994), and Wondra et al. (1995a) suggest a diet particle size of 700 µm as optimal when considering milling energy cost, growth performance, stomach morphology, and nutrient digestibility. In their review of the literature, Hancock and Behnke (2001) concluded that a 1.3% improvement in feed efficiency (gain:feed) could be achieved for each 100-µm reduction in mean particle size in corn or sorghum. Equating this to an increase in energy digestibility suggests that for each 100-µm reduction in mean particle size of corn or sorghum, apparent total tract energy digestibility increases by approximately 0.86 percentage units, which is equivalent to an increase of approximately 30 kcal DE per 100-µm particle size reduction (Owsley et al., 1981; Giesmann et al., 1990; Healy et al., 1994; Wondra et al., 1995a,b,c,d). Although it has been known for some time that decreasing particle size improves nutrient digestibility of oats (Crampton and Bell, 1946), information about the effect of mechanical processing on changes in fiber digestion and energy utilization of fibrous feeds is limited. In gestating sows fed diets containing 50% alfalfa meal, Nuzback et al. (1984) reported that decreasing the particle size from 646 µm to 434 µm improved dry matter, neutral detergent fiber, acid detergent fiber, hemicellulose, and cellulose digestibility, with energy digestibility increasing by 2.2 percentage units per 100-µm reduction in particle size (equivalent to approximately 97 kcal per 100-µm reduction in particle size). More recently, decreasing the particle size of several sources of distillers dried grains with solubles (DDGS) from 716 µm to 344 µm (Mendoza et al., 2010) or, in a single DDGS source, from 818 to 308 µm (Liu et al., 2011) increased energy digestibility equivalent to an increase of approximately 45 kcal DE for each 100-µm reduction in particle size.

Micronization is also a process to reduce particle size through the use of moisture, temperature, and mechanical pressure. The effect of micronization on pig performance or nutrient digestibility has been inconsistent. Some researchers have found improvements in performance or nutrient digestibility (Lawrence, 1973; Thacker, 1999; Owusu-Asiedu et al., 2002; Nyachoti et al., 2006), but others have not (Zarkadas and Wiseman, 2001; Valencia et al., 2008).

Thermal processing, with or without pressure, of diets may affect nutrient digestion and subsequent animal performance (Lundbald, 2009). One of these effects is a change in starch structure and the potential to denature α-amylase inhibitors. Heating in the presence of water causes a swelling process, resulting in crystalline disruption and gelatinization, and this has been shown to increase starch digestibility (Sun et al., 2006; Vicente et al., 2009). In contrast, if gelatinized starch is not rapidly cooled, but allowed to slowly recrystallize, it turns into an amorphous matrix called retrograde starch. Retrograde starch is sometimes miscalled resistant starch, but there are distinct differences (Bhandari et al., 2009). Both resistant and retrograde starch are resistant to enzymatic digestion in the small intestine, but can be broken down by hindgut microbes to volatile fatty acids, such that virtually no starch is found in feces (Heijnen and Beynen, 1997; Hedemann and Bach Knudsen, 2007). Thermal processing can also destroy protease inhibitors, which interfere with the digestion and metabolic utilization of proteins. Two of the best-known inhibitors are trypsin inhibitor and chymotrypsin inhibitor, which are present in legume seeds (i.e., soybeans, peas, and *Phaseolus* beans). Both of these inhibitors can be destroyed by proper heat processing techniques (Liener, 2000).

Extrusion and expander processing (heat and pressure processing) is utilized in the aquaculture and pet feed processing industries, and the benefits have been reviewed by Hancock and Behnke (2001). Recently, research with swine has shown that extrusion of corn improves ileal DM digestibility (Muley et al., 2007) and improves ileal and total tract nutrient digestibilities in diets containing field peas or flax plus field peas (Stein and Bohlke, 2007; Htoo et al., 2008). In contrast, expander processing of a pea-soybean meal–tapioca-based diet or a wheat-barley-soybean meal–canola meal-based diet had no effect on total tract nutrient digestibility (van der Poel et al., 1997) or pig performance (Callan et al., 2007). Reasons for the differences are not apparent.

The effect of pelleting diets on pig performance is variable, but overall it seems that gain and feed efficiency are improved by approximately 6% (Hancock and Behnke, 2001). Reasons for this improvement are multiple, including changes in physiochemical characteristics (i.e., starch gelatinization), increased bulk density, improved palatability, reduced fines and dust, decreased pathogen presence, improved nutrient digestibility, and/or reduced feed wastage. Pelleting of diets containing large amounts of corn fiber (corn gluten feed) has been shown to improve N balance, apparently because of the increased availability of tryptophan (Yen et al., 1971). Extruders and expanders are also used in the feed industry to improve pelleting efficiency and pellet quality (Lundbald et al., 2009), with some indication that expander conditioning improves gain and feed intake to a larger degree than does extruder processing, with some improvement in ileal amino acid digestibility, but not for dry matter, crude protein, or P (Lundbald, 2009).

ADDITIONAL PROSPECTS AND SOURCES OF INFORMATION

The application of various processing methods to improve nutrient digestibility of plant-based feed ingredients for swine and poultry has been studied for decades. However, with a large diversity and concentration of physical and chemical characteristics existing among feed ingredients, improvements in nutrient digestibility and pig performance diets will depend on understanding these characteristics in relation to how processing may impact the nutritional component in question. One of the primary purposes of processing is to reduce antinutritional factors that affect nutrient utilization and subsequent animal performance, while at the same time not causing inadvertent destruction of other needed dietary components. Excess heat and moisture can cause destruction of several nutrients, especially amino acids and this is discussed in Chapter 2. With the inverse relationship between fiber content and energy digestibility, it is logical that development of processing methods that improve fiber digestion, and thereby improve energy digestibility, may be beneficial, both metabolically and economically. Additional information on practical feed processing can be found in reviews by Hancock and Behnke (2001) and Richert and DeRouchey (2010).

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13

Digestibility of Nutrients and Energy

INTRODUCTION

Diets for swine are formulated by combining feed ingredients in such a way that the mixed diet meets the nutrient and energy needs of the animal. Chemical analyses of individual ingredients are used to calculate the assumed composition of the mixed diet. However, nutrients in different ingredients are not utilized with the same efficiency, and some dietary nutrients are excreted in the feces without contributing to the nutritional or energy status of the animal. It is, therefore, important that an estimate of the proportion of each nutrient that is absorbed by the pig is known and that the nutrients and energy that are absorbed from all the ingredients in the diet meet the nutritional needs of the animal.

The availability of dietary nutrients may be described as the proportion of nutrients that are absorbed from the intestinal tract in a form that is usable for metabolism or tissue synthesis (Batterham, 1992). However, nutrient availability is "an abstract concept, which cannot be measured, but it can be estimated" (Sibbald, 1987). Values for availability may be estimated using the slope-ratio assay, which provides values for the relative availability rather than for the absolute availability of a nutrient (Ammerman et al., 1995; Gabert et al., 2001). Slope-ratio assays are tedious and expensive to conduct and values that are additive in mixed diets are not always obtained (Gabert et al., 2001).

To overcome the difficulties and inaccuracies of determining and using values for relative availability, values for nutrient and energy digestibility are often used in feed formulation as a more practical way of assessing the quantities of nutrients and energy that are absorbed (Gabert et al., 2001; Stein et al., 2007). As a consequence, each ingredient needs to be characterized in terms of the digestibility of nutrients and energy, and it is important that nutrient and energy digestibility is expressed in units that are additive in mixed diets. Nutrient and energy digestibility can be expressed in numerous ways and consistency is, therefore, desirable. The objective of this chapter is to describe how the digestibility of amino acids, lipids, carbohydrates, phosphorus, and energy is determined. Additional information about the various techniques involved and alternative procedures with their advantages and disadvantages is contained in the comprehensive reviews by Adeola (2001), Gabert et al. (2001), and Stein et al. (2007).

CRUDE PROTEIN AND AMINO ACIDS

The protein value of a feed ingredient to pigs is determined by the composition and digestibility of the essential amino acids (AA) in that ingredient. These AA need to be supplied in the diet every day, and the quantities of dietary essential AA that are available for protein synthesis in the pig depend on the quantities of these AA that are absorbed from the intestinal tract. It is, therefore, necessary that the digestibility of AA in each feed ingredient be determined, and most diets fed to pigs are formulated on the basis of digestible AA in each ingredient. It is, however, recognized that if feed ingredients have been heat treated, some of the digestible AA may not be available for protein synthesis due to the changes in the structure of these AA caused by the Maillard reaction (Batterham, 1992; Moughan, 2003a, 2005; Finot, 2005; Pahm et al., 2009).

Amino acids are absorbed in the small intestine of the pig, and AA that are not absorbed prior to the distal ileum will enter the large intestine where they may be fermented by the large bowel microflora. Fermentation may result in both catabolism and synthesis of AA, but absorption of AA in the large bowel is negligible and undigested AA, along with AA synthesized by the microbes, are excreted in the feces. However, because of the microbial fermentation of AA entering the large intestine, the AA concentration in the feces does not accurately represent the AA that escaped absorption in the small intestine (Sauer and Ozimek, 1986). It is, therefore, necessary to estimate the disappearance of

AA from the small intestine, which may be accomplished by collecting digesta from the distal ileum. To gain access to ileal digesta, pigs have to be surgically modified, and several procedures may be used for this purpose (Sauer and de Lange, 1992; Moughan, 2003b). In North America, this is most often accomplished by surgically installing a T-cannula in the ileum 10-20 cm cranial to the ileal-cecal junction. The cannula allows collection of ileal fluids from the pig, but because total collection is not possible with this procedure, an indigestible marker, most often chromic oxide or titanium dioxide, has to be included in the diet to enable calculation of AA digestibility.

Ileal AA digestibility values are expressed as apparent ileal digestibility (AID) values or as standardized ileal digestibility (SID) values. Values for AID of AA are calculated by use of concentrations of AA and the indigestible marker in the diet and ileal digesta according to Eq. 13-1 (Stein et al., 2007):

$$\text{AID}\ (\%) = [1 - (\text{AA}_{digesta} / \text{AA}_{diet}) \times (\text{Marker}_{diet} / \text{Marker}_{digesta})] \times 100 \quad \text{(Eq. 13-1)}$$

where $\text{AA}_{digesta}$ and AA_{diet} represent the AA concentrations in the ileal digesta and diet dry matter (DM) (g/kg) and Marker_{diet} and $\text{Marker}_{digesta}$ represent the concentration of the indigestible marker in the diet and the digesta DM (g/kg), respectively.

Values for AID of AA are “apparent” values because they represent the apparently ileal-digested values, which are different from the truly digestible values for dietary AA because the quantities of AA that are collected from the distal ileum contain a mixture of undigested feed AA and AA of endogenous origin. The endogenous AA represent AA that were secreted into the intestinal tract in the form of enzymes, sloughed cells, mucoproteins, serum albumin, or other compounds (Nyachoti et al., 1997; Moughan et al., 1992; Jansman et al., 2002). The majority of these endogenous proteins are digested and the AA are reabsorbed from the small intestine. However, some of the endogenous proteins enter the large bowel without being digested, and the AA in these proteins are, therefore, losses to the animal and termed endogenous losses. Portions of the endogenous losses are secreted in response to the presence of DM in the intestinal tract of the pig. These AA contribute a greater proportion of the total ileal output of AA for feed ingredients with a low AA concentration than for feed ingredients with a greater AA concentration (Fan et al., 1994; Mosenthin et al., 2000). Thus, values for AID are dependent on the concentration of AA in the diet used to measure AID values (Donkoh and Moughan, 1994; Fan et al., 1994). As a consequence, values for AID measured in individual feed ingredients are not always additive in mixed diets (Stein et al., 2005). However, if values for AID are corrected for the endogenous AA that are secreted in response to the intake of DM by the animal, the influence of endogenous losses on AA digestibility can be minimized. To make this correction, it is necessary to determine the quantities of endogenous AA that are lost in response to the intake of DM by the animal (Mosenthin et al., 2000; Jansman et al., 2002). These endogenous losses are called basal endogenous losses, and they are usually determined in animals fed a protein-free diet and calculated according to Eq. 13-2 (Stein et al., 2007):

$$\text{IAA}_{end} = \text{AA}_{digesta} \times (\text{Marker}_{diet} / \text{Marker}_{digesta}) \quad \text{(Eq. 13-2)}$$

where IAA_{end} is the basal endogenous loss of an AA in grams per kilogram DM intake (DMI), $\text{AA}_{digesta}$ is the concentration of that AA in the ileal digesta (g/kg DM), and Marker_{diet} and $\text{Marker}_{digesta}$ are the marker concentrations in feed and digesta, respectively (g/kg DM).

Use of the protein-free diet to estimate basal endogenous losses of AA has been criticized for being unphysiological (Low, 1980; Hodgkinson et al., 2000). Alternative procedures to determine the basal endogenous losses such as the regression procedure, feeding enzymatically hydrolyzed casein, and feeding diets containing crystalline AA have been proposed (Nyachoti et al., 1997; Moughan et al., 1992; Mariscal-Landin and Reis de Souza, 2006). However, when comparing the different procedures, no clear differences among procedures in the estimates of basal endogenous losses of AA were observed (Jansman et al., 2002), and the protein-free diet is, therefore, the most commonly used procedure to estimate basal endogenous losses of AA. Correcting AID values for the basal endogenous losses yields SID values, as shown in Eq. 13-3 (Stein et al., 2007):

$$\text{SID}\ (\%) = \text{AID} + [(\text{basal IAA}_{end} / \text{AA}_{diet}) \times 100] \quad \text{(Eq. 13-3)}$$

where SID is the standardized ileal digestibility of an AA (%), basal IAA_{end} is the basal endogenous loss of that AA (g/kg DMI), and AA_{diet} is the concentration of that AA in the diet DM (g/kg).

Because the effects of basal endogenous losses are eliminated in the calculation of values for SID, these values are believed to be additive in mixed diets (Stein et al., 2005). As a consequence, in practical feed formulation, values for SID of AA are preferred.

The accuracy of the SID values that are determined for each feed ingredient relies on the assumption that AA that are absorbed from the small intestine are available for protein synthesis and that there is no microbial metabolism or microbial net synthesis of AA in the small intestine (Moughan, 2003a). As mentioned above, AA that are absorbed from heated proteins that have undergone the Maillard reaction, may not always be 100% available for protein synthesis, which may result in inaccuracies of the estimated values for the SID of AA in these ingredients

(Moughan, 2005). It is recognized that the majority of microbes in the intestinal tract of pigs reside in the large intestine, but it is also clear that there is some microbial activity in the small intestine (Smiricky et al., 2002) and it is likely that microbial catabolism and synthesis of AA take place in the small intestine. However, there are no definitive data to demonstrate a net synthesis or a net disappearance of AA as a result of microbial fermentation in the small intestine (Moughan, 2003a), and the microbial activity in the small intestine is, therefore, assumed to not influence absorption and utilization of dietary AA.

LIPIDS

Most diets fed to swine are not formulated on the basis of digestible lipids, and digestibility values for lipids are usually not included in formulation programs. However, lipids contribute to the absorption of energy from diets, and lipid digestibility is, therefore, sometimes determined in feed ingredients.

Digestion and absorption of lipids require sequential steps in the small intestine (i.e., emulsification, enzymatic hydrolysis, micelle formation, transport through the unstirred water layer, and absorption into the enterocytes) because lipids are poorly soluble in the aqueous environment in the small intestine (Bauer et al., 2005). Many factors influence lipid digestibility, and the apparent total tract digestibility (ATTD) of lipids in complete diets fed to pigs varies between 25 and 77% (Noblet et al., 1994). Microbes in the hindgut may synthesize lipids, which results in excretion of endogenous lipids in the feces. This is particularly true if high-fiber diets are fed because fiber promotes an increase in the intestinal microbial population, which results in a subsequent increase in the synthesis and loss of endogenous lipids (Kil et al., 2010). Lipid digestibility is, therefore, more accurately determined as the ileal digestibility rather than the total tract digestibility. Values for the AID of lipids are determined the same way as values for the AID of AA, and an indigestible marker is included in the diet.

The concentration of dietary lipids affects the values for the AID of lipids the same way as the concentration of dietary AA influences the AID of AA (Kil et al., 2010) because of the influence of endogenous lipids on the calculated values for AID. To minimize this effect, the ileal endogenous losses of lipids need to be estimated. Unlike the situation for AA, procedures for determining the basal ileal endogenous losses of lipids have not been proposed, and the SID of lipids is usually not determined. However, a regression procedure has been used to estimate ileal endogenous losses of lipids (Jørgensen et al., 1993; Kil et al., 2010), but values for the total rather than the basal ileal endogenous losses of lipids are determined using this procedure. By correcting values for the AID of lipids for the total endogenous losses, values for the true ileal digestibility (TID) of lipids are calculated according to Eq. 13-4:

$$\text{TID (\%)} = \text{AID} + [(\text{total IL}_{end} / \text{L}_{diet}) \times 100] \quad \text{(Eq. 13-4)}$$

where total IL_{end} is the total ileal endogenous loss of lipids (g/kg DMI) and L_{diet} represents the lipid concentration in the diet DM (g/kg). Values for the TID of lipids may also be determined directly from the slope of the regression line if the regression procedure is used (Jørgensen et al., 1993; Kil et al., 2010).

Lipids in feed ingredients may be analyzed as ether extract or as acid-hydrolyzed ether extract. Values for acid-hydrolyzed ether extract are usually greater than values for ether extract because the acid hydrolysis step liberates lipids that are bound to minerals (Sanderson, 1986). As lipids may form complexes with minerals in the intestinal tract of animals, values for acid hydrolyzed ether extract are believed to be more accurate in determining lipid digestibility of feed ingredients and diets.

In conclusion, if lipid digestibility is determined, values for the TID of lipids are preferred because these values most accurately reflect the absorption of dietary lipids. Values for the TID of lipids are not influenced by the concentration of lipids in the diet. Unlike values for the total tract digestibility of lipids, TID values are not influenced by the microbial synthesis of lipids that often takes place in the hindgut of pigs. It is, therefore, believed that values for the TID of lipids are additive in mixed diets.

CARBOHYDRATES

Diets fed to swine are not usually formulated on the basis of digestible carbohydrates but, as is the case for lipids, carbohydrates contribute to the quantity of energy that a pig absorbs from a given diet. To estimate the concentration of energy that a pig may absorb from a diet, estimates of the digestibility of the carbohydrates in the diet are needed (Noblet et al., 1994). Carbohydrates include sugars and disaccharides, starch and glycogen, and dietary fiber, and the carbohydrates within each of these three fractions are digested or fermented to a different degree. As a consequence, the digestibility needs to be characterized for each group of carbohydrates.

Disaccharides

Diets often contain monosaccharides and sucrose, and diets for young pigs may also contain lactose. Sucrose and lactose are digested by the brush border enzymes in the small intestine and the resultant monosaccharides are rapidly absorbed along with dietary monosaccharides by both active and passive transport mechanisms (Englyst and Hudson, 2000). Because this process is very effective, it is generally assumed that disaccharides are digested with an efficiency of 100% before the end of the small intestine (van Beers et al., 1995) and the digestibility of these disaccharides is usually not determined. However, if it is necessary to determine the digestibility of disaccharides, AID values can be determined as outlined for AA. There is no evidence of any endogenous secretion of disaccharides so there is no need to correct for endogenous losses, and values for SID or TID of disaccharides are, therefore, not calculated.

Starch and Glycogen

Swine diets usually contain large quantities of starch, whereas glycogen is present in the diets only if meat byproducts are included in the diet. Even if meat byproducts are included, the concentration of glycogen in the diet is negligible. As for disaccharides, most dietary starch is easily digested in the small intestine by pancreatic and intestinal amylase in combination with intestinal maltase and isomaltase (also called α-dextrinase; Groff and Gropper, 2000). Starch digestion is usually an efficient process, and between 90 and 95% of the starch in most feed ingredients is digested before the end of the small intestine (Bach Knudsen, 2001). The resulting glucose is absorbed and contributes to the energy status of the pig. Starch that is not digested in the small intestine (i.e., resistant starch) is readily fermented in the large intestine. The concentration of starch in the feces in pigs fed commercial diets is usually very low, resulting in a total tract digestibility of starch that usually is greater than 99% (Stein and Bohlke, 2007). The exception to this is if the ingredients in the diets are not ground to an acceptable particle size that will allow enzymes and microbes access to the starch for digestion or fermentation.

Because of the fermentation of undigested starch in the large intestine, starch digestibility needs to be determined at the end of the small intestine, and values for the AID of starch need to be determined as explained for AA, lipids, and disaccharides. As is the case for disaccharides, there are no known endogenous secretions of starch into the intestinal tract and AID values are not corrected for endogenous losses. Consequently, values for SID and TID of starch are not calculated.

Starch that is not digested in the small intestine is called resistant starch. The quantity of resistant starch in a feed ingredient may be measured using enzymatic procedures that mimic the digestion in the small intestine. However, if the in vivo AID value of starch has been determined, the amount of resistant starch in the ingredient may be calculated by subtracting the AID value of starch from 100. The energy value of resistant starch is less than the value of starch that is digested in the small intestine because fermentation of resistant starch results in absorption of short-chain fatty acids rather than glucose, and the efficiency of utilization of energy in the form of short-chain fatty acids is less than that of glucose (Black, 1995).

Dietary Fiber

The total quantity of dietary oligosaccharides, resistant starch, nonstarch polysaccharides, and lignin is collectively characterized as "dietary fiber." By definition, dietary fiber is not digested by enzymes in the small intestine and includes all the dietary carbohydrates that resist small intestinal enzymatic digestion. Some components of dietary fiber are fermented in the small intestine, whereas other components are fermented in the large intestine (Urriola et al., 2010). Regardless of the site of fermentation, the only energy-yielding end products that are absorbed after fermentation are short-chain fatty acids. As a consequence, there is no difference in the energy contribution of fiber related to the site of fermentation. To accurately determine the energy contribution of dietary fiber, total tract disappearance of dietary fiber has to be determined. Although it is recognized that components of endogenous secretions may be analyzed as dietary fiber (Cervantes-Pahm, 2011), basal or total endogenous losses of fiber are usually not determined. As a consequence, the contribution of absorbable energy from dietary fiber is usually determined based on values for the apparent total tract disappearance of fiber.

PHOSPHORUS

Absorption of P occurs in the small intestine, and endogenous P is also secreted into the small intestine (Fan et al., 2001). The large intestine plays no measurable role in P homeostasis, and there seems to be neither a net absorption of P from the large intestine nor a net secretion of endogenous P into the large intestine (Bohlke et al., 2005). Values for the AID of P are, therefore, not different from values for the ATTD of P (Fan et al., 2001; Bohlke et al., 2005; Dilger and Adeola, 2006). Because values for total tract digestibility are easier and less expensive to determine than values for AID, values for P digestibility are usually based on total tract digestibility and ATTD values can be calculated using Eq. 13-5 (Almeida and Stein, 2010):

$$\text{ATTD of P (\%)} = [(P_{intake} - P_{output}) / P_{intake}] \times 100 \qquad \text{(Eq. 13-5)}$$

where P_{intake} and P_{output} are expressed as grams per day or in grams for the entire collection period.

Although relatively small, endogenous P losses (EPL) significantly influence values for the ATTD of P, and values for the ATTD of P are, therefore, influenced by the dietary concentration of P (Fan et al., 2001; Shen et al., 2002; Ajakaiye et al., 2003) the same way as values for the AID of AA and lipids are affected by the dietary concentration of AA and lipids, respectively. Values for the ATTD of P may, therefore, not always be additive in mixed diets, which creates difficulties in practical diet formulation, because additivity of digestibility values among feed ingredients is assumed. Consequently, corrections for EPL are needed. However, reported estimates of total EPL vary among experiments (Shen et al., 2002; Dilger and Adeola, 2006; Pettey et al., 2006), and based on published experiments, it is not possible to determine the total EPL in pigs. In contrast, estimates of basal EPL are much less variable and average approximately 190 mg P per kilogram of DMI (Traylor et al., 2001; Stein et al., 2006; Widmer et al., 2007; Almeida and Stein, 2010). Basal EPL are easily calculated from P excretion of pigs fed a P-free diet according to Eq. 13-6 (Almeida and Stein, 2010):

$$\text{Basal EPL (mg/kg DMI)} = [(P_{output} / \text{DMI}) \times 1{,}000 \times 1{,}000] \quad \text{(Eq. 13-6)}$$

where basal EPL is the basal endogenous P loss (mg/kg DMI), P_{output} is the daily fecal output of P (g), and DMI is the daily intake of feed DM (g).

By subtracting the basal EPL from the fecal output of P in pigs fed a P-containing diet, the standardized total tract digestibility (STTD) of P in that diet is calculated according to Eq. 13-7 (Almeida and Stein, 2010):

$$\text{STTD (\%)} = \{[P_{intake} - (P_{output} - \text{basal EPL})] / P_{intake}\} \times 100 \quad \text{(Eq. 13-7)}$$

where STTD (%) is the standardized total tract digestibility of P; P_{intake} and P_{output} are the daily intake and output, respectively, of P (g); and basal EPL is the basal EPL per kilogram DMI (g) multiplied by the daily DMI of the pig.

If the ATTD of P has already been determined, this value may be converted to STTD by correcting the ATTD value for the basal EPL according to Eq. 13-8:

$$\text{STTD (\%)} = \text{ATTD} + [(\text{basal EPL} / P_{diet}) \times 100] \quad \text{(Eq. 13-8)}$$

where basal EPL is the basal EPL (g/kg DMI) and P_{diet} is the concentration of P in grams per kilogram of diet DM.

As mentioned, the basal EPL is approximately 190 mg/kg DMI and this value is relatively constant among experiments and among pigs of different weights (Baker, 2011). As a consequence, there is no need to determine basal EPL in the same group of pigs as those used to determine the ATTD of P in a specific ingredient. Instead, ATTD values can be corrected for the basal EPL by using a constant value for basal EPL of 190 mg/kg DMI. This approach allows for calculation of STTD values for all ingredients with a known ATTD value. By using values for the STTD of P in practical diet formulation, additivity among feed ingredients is achieved, and diets are, therefore, more accurately formulated if values for STTD of P are used rather than values for ATTD of P.

ENERGY

The energy that a pig obtains from a diet is the sum of the energy produced by oxidation of protein, lipids, and carbohydrates. The gross energy (GE) in a diet is determined by bomb calorimetry. The digestible energy (DE) in a diet can be directly determined by subtracting the fecal output of GE from the intake of GE for pigs fed that diet. Alternatively, the digestibility of energy in diets or feed ingredients can be determined by calculating the ATTD of energy in the ingredient. Eq. 13-5, which is used to calculate the ATTD of P, may also be used to calculate the ATTD of GE. By multiplying the ATTD of energy by the GE in the diet, the DE in the diet is determined. As a consequence, total collections of feces from pigs fed the diet or ingredient are needed to calculate the DE of a diet or a feed ingredient. This can be achieved by placing pigs in metabolism cages. Feed intake and fecal output are usually determined over a 5-day period following an adaptation period of 5-10 days. To ensure that the feces that are collected originate from the feed that was fed during the 5-day collection period, a start marker needs to be included in the diet at the beginning of collection and fecal collection starts when the marker appears in the feces (Widmer et al., 2007). Likewise, a stop marker needs to be included in the diet at the conclusion of the collection period, and fecal collection ceases when this marker appears in the feces (Adeola, 2001; Widmer et al., 2007).

If urine is also collected during the period when feces are collected, the total excretion of energy from the urine can be determined for the collection period. By subtracting this value from the DE of the diet, the quantity of energy that was metabolized by the pig is calculated. This value is called the metabolizable energy (ME). For most feed ingredients, the ME is between 92 and 98% of the DE. The major energy-containing component in urine is nitrogen and it is recognized that experimental diets containing different concentrations of protein may result in different quantities of nitrogen excreted in the urine. This is particularly true when test ingredients contain proteins with an amino acid profile substantially different from the requirement profile. The ME values for these ingredients may be underestimated. To ameliorate this problem, ME values are sometimes adjusted to a 50% nitrogen retention value because it is assumed that in balanced diets, approximately 50% of the digested nitrogen is retained in the body (Noblet et al., 2004). Values for nitrogen-corrected ME, in which the urine nitrogen output is adjusted to 50% nitrogen retention, are sometimes calculated (Cozannet et al., 2010).

Values for energy digestibility of some feed ingredients may be influenced by the age of the pigs and values obtained with pigs of a specific weight are not always representative of values for pigs of different weights (Le Goff and Noblet, 2001; Jørgensen et al., 2007; Cozannet et al., 2010). This is true specifically for feed ingredients that have high concentrations of nonstarch polysaccharides (LeGoff and Noblet, 2001). As a consequence, it has been suggested that different energy values are assigned to each feed ingredient based on the group of pigs the ingredient is fed to (Noblet and van Milgen, 2004). There is, however, a lack of data to demonstrate the exact energy values that different groups of pigs can utilize from each feed ingredient, which precludes utilization of age-specific energy values in feed evaluation systems for growing pigs. A system in which specific energy values are assigned to sows and a different value to all other groups of pigs, has, however, been suggested (Sauvant et al., 2004).

The breed of pigs that is used to estimate energy digestibility values may also affect the estimates of energy concentrations in feed ingredients, and it is recognized that many indigenous breeds of pigs have greater digestibility of fiber and energy than pigs typically used in commercial production (Kemp et al., 1991; Ndindana et al., 2002; Len et al., 2006; von Heimendahl et al., 2010). However, evidence of differences in energy digestibility among commercial breeds of pigs (e.g., Large White, Landrace, Duroc, and Hampshire) has not been published, and it is assumed that energy values obtained with one breed of pigs are also representative of other breeds.

Energy digestibility of some feed ingredients is also influenced by the particle size that is used to determine the digestibility (Healy et al., 1994), and this is true in growing pigs as well as sows (Wondra et al., 1995a,b). In general, the smaller the particle size, the greater is the digestibility of energy and there are, therefore, economic implications of reducing the particle size of feed ingredients (Borg, 2008). There are, however, also disadvantages of reducing the particle size of feed ingredients because a reduced particle size may cause increased stomach ulceration and increase the size of the mucin granules in the crypts in the intestinal tract (Brunsgaard, 1998; Hedeman et al., 2005). A particle size of 400 to 600 µm is most often used in practical swine production, and it is recommended that such a particle size is also used in experiments in which the digestibility of energy is determined.

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14

Influence of Nutrition on Nutrient Excretion and the Environment

INTRODUCTION

Maximization of pig performance has traditionally been the goal of swine producers and nutritionists. Diets are generally formulated to achieve this goal by meeting minimum requirements at a minimal cost (least cost formulation), with limited concern over excesses of many nutrients. Formulating diets to account for (1) meeting the requirements for a group of animals, (2) the compositional variation of ingredients, and (3) the variation in the digestibility and availability of nutrients within a feedstuff can all result in excesses of many nutrients in a diet provided to the animal. Consequently, oversupplementation of diets with nutrients to ensure maximum pig performance can result in an excessive amount of nutrients being excreted in the feces and urine and, ultimately, into the environment. Levels of dietary nutrients (i.e., crude protein, various minerals, and electrolyte balance) may affect water consumption and subsequent excretion and manure output. Research results indicate, however, that the intake of nutrients explains only a small part of the variation in voluntary water intake (Mroz et al., 1995; Shaw et al., 2006).

Requirements for most nutrients decrease (as a percentage of the diet) as pigs increase in body weight; thus, frequent changes in diet formulation to match more closely nutrient needs (phase feeding) will result in reduced excesses (or deficiencies) of nutrients relative to the ever-changing requirements, and, consequently, reduce nutrient excretion (Boisen et al., 1991; Roth and Kirchgessner, 1993c). In combination with phase feeding, separate-sex feeding allows nutrient needs of genders to be met even more precisely, thereby reducing nutrient excretion (Campbell et al., 1985; Campbell and Taverner, 1988).

Associated with improving the utilization of nutrients for animal production is that the efficiency of animal performance follows the principle of diminishing returns in response to nutrient input (Heady et al., 1954; Combs et al., 1991; Gahl et al., 1995). As such, nutritionists may need to formulate diets closer to a predefined response level, because the benefit of an additional unit of nutrient increases at a decreasing rate, and nutrient costs increase at an increasing rate as the animal approaches maximum performance. As the cost of many ingredients (nutrients) and disposing of nutrients increase, the level of each nutrient fed to pigs will need to be closer to their constantly changing daily requirements.

Within the variety of ingredients fed to swine, there is a moderate variation in the availability of these nutrients to the animal, with undigested or unavailable nutrients being excreted. Thus, one method to reduce nutrient loss is to utilize ingredients with a higher level of nutrient digestibility or availability, thereby allowing a greater proportion of nutrients to be absorbed and potentially utilized for productive purposes. However, the issue of maximum nutrient digestibility/availability has to be weighed relative to feedstuff cost, limits of feedstuff inclusion in feed formulation, and the animal's physiological ability to consume the feedstuff (e.g., gut fill relative to fibrous feedstuffs or reduction in enzyme activity such as lactase in older pigs). Another opportunity to improve digestibility is through the use of exogenous enzymes targeted toward improving the digestibility of specific complexes within feed ingredients. The most effective of these seems to be the use of phytases to release phytin phosphorus, but other enzymes include proteases for proteins, lipases for lipids, and various carbohydrases for complex carbohydrates. In addition, utilization of different mineral sources (sulfates vs. oxides) or mineral complexes (e.g., chelates and proteinates) may increase the availability of certain nutrients to the animal. Lastly, ingredients containing antinutritional factors such as tannins (Brand et al., 1990), gossypol (Knabe et al., 1979; Mosenthin et al., 1993), mycotoxins (Goyarts and Danicke, 2005), and trypsin inhibitors (Herkelman et al., 1992; Barth et al., 1993) have also to be considered for their effect on nutrient digestion.

A second approach to reduce nutrient excretion is to optimize the utilization of absorbed nutrients. An example of this is the judicious use of ingredients susceptible to the

Maillard reaction (changes can occur to lysine that have little effect on digestibility but markedly affect utilization of absorbed lysine; Batterham, 1992). In addition, providing an optimal balance of amino acids for protein synthesis either through complementary feedstuffs or crystalline amino acids will lead to improved nitrogen utilization (Batterham and Bayley, 1989; Buraczewska and Swiech, 2000; Baker, 2004; Yen et al., 2004). For minerals, proper Ca:P ratios are known to be important for the absorption and utilization of dietary calcium and phosphorus (Selle et al., 2009), and for various trace minerals, potential interactions affecting digestion and absorption have to also be considered (Davies, 1979; Underwood, 1981; Fairweather-Tait and Hurrell, 1996; Baker, 2008).

The success of all strategies to reduce nutrient excretion is ultimately dependent on three main factors: (1) an accurate estimate of the nutrient requirements of the class of pigs in question, (2) the accuracy of compositional information of each feedstuff, and (3) the digestibility or availability of each nutrient within each feedstuff.

NITROGEN

In swine, retention of dietary nitrogen is far from 100%, ranging from 30 to 60% of intake (Kirchgessner et al., 1994; Otto et al., 2003a; van Kempen et al., 2003). Formulating feeds with only natural feedstuffs to meet amino acid requirements results in large excess of essential and nonessential amino acids. If undigested, they are excreted largely as fecal microbial nitrogen; if absorbed and not required for a specific function, they are catabolized and excreted largely as urinary urea nitrogen. Utilization of various feedstuffs and crystalline amino acids in conjunction with established requirements and the use of the ideal protein concept can allow for amino acid requirements to be met with a reduced intake of dietary protein. Although reduction of dietary protein has minimal, if any, influence on pig performance and lean tissue deposition provided that crystalline amino acids are used to balance any amino acid limitations, the effect on nitrogen excretion can be dramatic. A summary of 33 swine metabolism data sets indicates that for each 1 percentage unit reduction in crude protein (but balanced for amino acid limitations) nitrogen excretion is reduced by approximately 8%, regardless of body weight (Kerr, 2003). This is similar to the 8.7% reported by Leek et al. (2005), but slightly greater than the 6.7% reported by Leek et al. (2007). This reduction in nitrogen excretion can have far-reaching results. Manure nitrogen will be reduced, which can affect how much can be applied to soils for agronomic purposes and, thus, may affect the amount of nitrogen in water runoff or percolation (Misselbrook et al., 1998). In addition, dietary crude protein intake influences subsequent ammonia emissions from manure (Latimier et al., 1993, von Pfeiffer, 1993; Kreuzer et al., 1998; Otto et al., 2003b; Portejoie et al., 2004; Velthof et al., 2005; Panetta et al., 2006; Le et al., 2009). The reduction in ammonia emission may be similar to (Hayes et al., 2004; Leek et al., 2007) or greater than (Canh et al., 1998b; Panetta et al., 2006) the 8% reduction in nitrogen excretion described by Kerr (2003). The higher values reported by Canh et al. (1998b) and Panetta et al. (2006) are supported by the observation that nitrogen recovery in nitrogen balance trials may overestimate nitrogen retention because of ammonia losses during fecal and urine collections if proper techniques are not followed (Just et al., 1982; van Kempen et al., 2003). Reductions in ammonia emissions will not only have potential environmental impacts, but also animal health and productivity may be improved. Although ammonia levels in swine production facilities rarely exceed 30 ppm even during periods of low ventilation (Sun and Hoff, 2010, 2011), it has been shown that pigs kept in an ammonia-contaminated environment (50 ppm) had a greater lung weight, lungs that contain 50% more bacteria than lungs of pigs kept in a room with filtered air, and decreased growth (Drummond et al., 1978, 1980; Donham, 1991).

Another issue is the route by which nitrogen is excreted, namely fecal vs. urinary. Although net excretion of nitrogen may not change, increasing the dietary content of resistant starch, indigestible oligosaccharides, or nonstarch polysaccharides can lead to increased bacterial proliferation because of an increase in fermentable carbohydrates in the lower bowel. This results in a shift of urinary nitrogen excretion to fecal nitrogen excretion in the form of microbial protein (Canh et al., 1997; Younes et al., 1997; Bakker and Dekker, 1998; Zervas and Zijlstra, 2002; Hansen et al., 2007), which has also been shown to reduce ammonia emissions (Canh et al., 1998c,d; Kreuzer et al., 1998).

CALCIUM AND PHOSPHORUS

Of the macrominerals, calcium and phosphorus are two of the most studied. Given that only 20 to 50% of the calcium or phosphorus consumed is retained for bodily functions (Kornegay and Harper, 1997), a large amount of these two minerals is excreted in manure. Calcium and phosphorus digestibility can be affected by a variety of factors, including mineral source (Combs and Wallace, 1962), feedstuff selection (Bohlke et al., 2005; Pedersen et al., 2007), other mineral levels (Stein et al., 2008), and body weight (Kemme et al., 1997a,b). In addition, the Ca:P ratio may affect not only the calcium or phosphorus digestibility (Vipperman et al., 1974), but also calcium or phosphorus retention (Crenshaw, 2001; Selle et al., 2009). In many plant-based feedstuffs, phosphorus is mainly found in the form of phytin phosphorus and is largely unavailable to nonruminant animals (Jongbloed and Kemme, 1990; Cromwell and Coffey, 1991; Pallauf and Rimbach, 1997), leading to a large amount of phosphorus that cannot be digested by the pig. However, the use of exogenous phytase to release phytin phosphorus has been shown in many experiments to improve phosphorus digestibility (Simons et al., 1990; Cromwell, 2002; Selle and Ravindran, 2008). The magnitude of this improvement is influenced by the source and level of phosphorus, Ca:P ratio, animal body weight, and the amount and type of phytase added (Kornegay, 1996; Selle and Ravindran, 2008; Kerr et al., 2010). Consequently, improving the digestibility and utilization of digested calcium and phosphorus, in combination with matching their supply as closely as possible to requirements for specific production systems, will reduce their excretion into the environment.

COPPER, IRON, MANGANESE, MAGNESIUM, POTASSIUM, AND ZINC

Retention of trace minerals from various practical diets by swine ranges from 5 to 40% for copper (Combs et al., 1966; Apgar and Kornegay, 1996), 5 to 40% for iron (Kornegay and Harper, 1997; Houdijk et al., 1999), < 10% for manganese (Kornegay and Harper, 1997), 15 to 60% for magnesium (Partridge, 1978; Dove, 1995), 5 to 20% for potassium (Mroz et al., 2002), and 5 to 40% for zinc (Houdijk et al., 1999; Rincker et al., 2005). In addition, although high levels of dietary copper or zinc have been shown to improve animal performance (Smith et al., 1997; Hill et al., 2000), approximately 90-95% of these minerals are ultimately excreted (Apgar and Kornegay, 1996; Veum et al., 2004; Buff et al., 2005). Consequently, a large percentage of these consumed minerals end up in manure, and if only a small portion is required for production of forages or crops, they have the potential to be in excess of agronomic needs, ending up as environmental contaminants. The soil does, however, have a large capacity to accumulate some minerals with no apparent negative impact on subsequent crop yields (Payne et al., 1988; Anderson et al., 1991).

SULFUR

Unlike the extensive understanding of sulfur amino acid metabolism (du Vigneaud, 1952; Shoveller et al., 2005; Baker, 2006), inorganic sulfur requirements have received little attention, other than the recognition that they may be required under special nutritional circumstances (Lovett et al., 1986) or concerns about high concentrations of sulfates in water (Anderson and Stothers, 1978; Paterson et al., 1979; Veenhuizen et al., 1992; Anderson et al., 1994). High excretion of sulfur (via dietary addition of $CaSO_4$) has been shown to reduce urine and manure pH, resulting in decreased ammonia emission (Canh et al., 1998a; Mroz et al., 2000), although this may be modulated by the level of dietary protein (Velthof et al., 2005). However, because various feedstuffs and minerals have elevated levels of total sulfur (Kerr et al., 2008), and because retention of total sulfur intake is approximately 65% (Shurson et al., 1998), sulfur excretion can have an impact on the soil, water, and air environment. Indeed, it is well known that various sulfur gasses can be emitted from animal manures (Banwart and Bremner, 1975), and increased dietary sulfur has been shown to increase sulfur-containing odorants (Sutton et al., 1998; Whitney et al., 1999; Apgar et al., 2002; Eriksen et al., 2010; Li et al., 2011). Unlike the relationship between nitrogen excretion and ammonia emissions (Latimier et al., 1993; von Pfeiffer, 1993; Panetta et al., 2006), however, there is no clearly defined relationship between sulfur excretion and volatile sulfur emissions.

CARBON

Although carbon is the fundamental element in energy-containing ingredients (namely starch, fats/oils, and non-starch polysaccharides) and is considered in indirect calorimetery experimentation, it is not considered in typical nutrient balance trials. Balance trials conducted in livestock generally focus on dry matter, energy, fat, or carbohydrate utilization. The ability of an animal to digest a feedstuff to yield energy (measured in terms of digestible, metabolizable, or net energy) to be used for maintenance and productive purposes is measured. Several publications on protein, fat, and mineral composition of swine (Mahan and Shields, 1998; Wiseman et al., 2009; Peters et al., 2010) have not included a direct measure of carbon. However, given the basis of carbon as a fundamental element in energy metabolism as well as gaseous emissions, its balance is an important consideration when assessing environmental impact.

Typically, whole-body composition is partitioned into ash, lipid, moisture, and protein (Shields et al., 1983; Wagner et al., 1999). Application of elemental estimates of body protein (carbon, 53%; hydrogen, 7%; oxygen, 23%; nitrogen, 16%) and body lipid (carbon, 76%; hydrogen, 12%; oxygen, 12%; nitrogen, < 1%) (Kleiber, 1961) to body growth curves and compositional estimates (Wagner et al., 1999) allows the estimation of whole-body carbon. Estimation of 40% carbon for a typical diet (Kerr et al., 2006) or computation of total dietary carbon from its protein, carbohydrate, and lipid content along with feed intake, an estimated respiratory quotient (adjustment of body growth for lean:fat deposition ratio), and carbon digestibility (estimated from feed, dry matter, or energy digestibilities) enable the estimation of carbon intake and retention, and, subsequently, carbon excretion. Recently, Kerr et al. (2006) reported that the carbon content of manure was approximately 0.9%, such that 6.5% of the total intake of dietary carbon ended up in stored manure. Increasing dietary fiber consumption has not only been shown to increase total manure output because of lower digestibility of dietary fiber (Graham et al., 1986; Canh et al., 1998d; Kreuzer et al., 1998; Burkhalter et al., 2001; Kerr et al., 2006). Furthermore, increasing dietary fiber also increases manure carbon as a percent of dietary carbon (Kerr et al., 2006), where it can have variable agronomic impacts (Unger and Kaspar, 1994;

Vitosh et al., 1997; Misselbrook et al., 1998; Sorensen and Fernandez, 2003).

DIET FORMULATION AND GASEOUS EMISSIONS

Gaseous emissions from swine manure are the result of microbial action on undigested feed products, endogenous animal secretions, and nutrients in excess of animal needs (Mackie et al., 1998; Zhu and Jacobson, 1999; Le et al., 2005) and include both "odorous" and "nonodorous" gasses. The list of odorous gasses is extensive (Spoelstra, 1980; Yasuhara et al., 1984; O'Neill and Phillips, 1992) but can be categorized into four major groups: fatty acids (i.e., acetic acid, $C_2H_4O_2$; propionic acid, $C_3H_6O_2$; butyric acid, $C_4H_8O_2$; isobutyric acid, $C_4H_8O_2$; isovaleric acid, $C_5H_{10}O_2$; n-valeric acid, $C_5H_{10}O_2$), phenolics (i.e., phenol, C_6H_6O; *p*-cresol, C_7H_8O; 4-ethyl phenol, $C_8H_{10}O$), sulfur compounds (i.e., hydrogen sulfide, H_2S; dimethyl trisulfide, $C_2H_6S_3$), and nitrogen compounds (i.e., ammonia, NH_3; indole, C_8H_7N; 3-methyl indole, C_9H_9N). The nonodorous compounds can be listed largely as greenhouse gasses (i.e., nitrous oxide, N_2O; methane, CH_4; carbon dioxide, CO_2). With odorants, the sense of smell is inherently complex such that often concentrations of specific gaseous emissions have to be paired with their detection thresholds to understand the potential impact on "odor" (Devos et al., 1990; Le et al., 2005) depending on whether samples are taken downwind (Wright et al., 2005) or above a mixed slurry (Blanes-Vidal et al., 2009). Likewise, greenhouse gasses have to be related to their carbon dioxide equivalency (IPCC, 2001) to have a true understanding of the potential impact of greenhouse gas reduction.

Information about the impact of feeding reduced crude protein diets on nonammonia emissions or odor is sparse and inconclusive. Hobbs et al. (1996), Shriver et al. (2003), and Le et al. (2008, 2009) have reported that pigs fed reduced crude protein, amino acid–supplemented diets resulted in manure with lower short-chain fatty acid concentrations, whereas Cromwell et al. (1999) and Otto et al. (2003b) reported increased total short-chain fatty acid concentrations in the manure from pigs fed a reduced dietary crude protein, amino acid–supplemented diet. Others (Obrock-Hegel, 1997; Sutton et al., 1999; Leek et al., 2007) reported essentially no difference in volatile organic compound concentrations when pigs were fed diets with various crude protein concentrations. It has been shown that lowering dietary crude protein decreases (Hayes et al., 2004; Le et al., 2007; Leek et al., 2007), increases (Cromwell et al., 1999; Otto et al., 2003b), or has no effect (Obrock-Hegel, 1997; Clark et al., 2005; Le et al., 2008, 2009) on "odor" emissions. Thus, there is currently no consensus on the effect of reduced crude protein diets on volatile organic compound concentrations or odor offensiveness.

Information about the effect of feeding low-crude protein, amino acid–supplemented diets on greenhouse gas emission is likewise incomplete. Velthof et al. (2005) observed that emission of CH_4 was lower when pigs were fed low-crude protein diets, while N_2O emissions were not different. In contrast, Clark et al. (2005) indicated that manure generated from pigs' low-protein diets resulted in increased CO_2 and CH_4 emissions, with no change in N_2O emission. Kerr et al. (2006) reported that reducing dietary crude protein did not affect the emission of CH_4 from the manure storage containers, but did increase N_2O emission, whereas Le et al. (2009) reported no impact on any of the greenhouse gasses (CH_4, N_2O, or CO_2).

Altering the dietary content of indigestible oligosaccharides, nonstarch polysaccharides, or resistant starch in diets can lead to increased bacterial proliferation in the cecum and hindgut of nonruminants, with products of this fermentation being short-chain fatty acids (acetate, propionate, and butyrate, with trace amounts of isobutyrate, valerate, and isovalerate) and various other gasses (CO_2, CH_4, and H_2) (Eastwood, 1992; Annison and Topping, 1994; Jensen and Jorgensen, 1994; van der Meulen et al., 1997). It has been reported that supplementation of feedstuffs containing these components results in modifications of manure short-chain fatty acid concentrations (Canh et al., 1997, 1998c,d; Sutton et al., 1999; Shriver et al., 2003; Lynch et al., 2007a; Le et al., 2008), with variable effects on fecal or manure odor (DeCamp et al., 2001; Miller and Varel, 2003; Rideout et al., 2004; Willig et al., 2005; Garry et al., 2007; Le et al., 2008; O'Shea et al., 2010).

Information about the influence of dietary fiber on greenhouse gas emissions is conflicting. Using respiratory chambers, Galassi et al. (2004) reported that wheat bran had no effect on CH_4 emissions, whereas supplemental beet pulp increased CH_4 emissions, relative to pigs fed a control diet. Velthof et al. (2005) reported that emission of CH_4 increased with increased dietary levels of dietary nonstarch polysaccharides, with no impact on N_2O. In contrast, Clark et al. (2005) reported that supplementing the diet with 20% beet pulp reduced CO_2 emission, but had no impact on CH_4 or N_2O emissions. Kerr et al. (2006) reported that supplementing the diet with soybean hulls as a source of cellulose increased the concentration of N_2O, but did not affect CH_4. There may be a closer relationship between CH_4 production and fermentable dietary fiber, as both Kirchgessner et al. (1991) and Jorgensen (2007) reported. Even though CH_4 production by nonruminant animals is lower than that produced by ruminants (Jensen, 1996), environmental conditions may necessitate that this be considered in future diet formulations.

Numerous feed additives have been included in diets in an effort to reduce ammonia, hydrogen sulfide, or odor emissions from swine production facilities. These products range from plant extracts (Colina et al., 2001; Rideout et al., 2004; Panetta et al., 2005; Lynch et al., 2007b; Windisch et al., 2008; Biagi et al., 2010), organic acids (Eriksen et al., 2010; Halas et al., 2010), pre- or probiotics (Wang et al., 2009; O'Shea et al., 2010), plant-derived oils (Varel, 2002; Michiels et al., 2009), humic compounds (Ji et al., 2006), and acidifying calcium salts (Canh et al., 1998a) to trace minerals (Armstrong et al., 2000). A review of this literature, however, is beyond the scope of this publication.

INTEGRATED APPROACHES

In general, improving nutrient digestion and the efficiency of feed (nutrient) utilization will decrease the loss of nutrients by the animal (Henry and Dourmad, 1992). Increases in feed efficiency can be achieved by improved genetics (Campbell and Taverner, 1988; Bark et al., 1992); improved environmental conditions (Verstegen et al., 1973); proper formulation of diets using high-quality ingredients; feeding processing, such as pelleting and fine grinding of feed (Yen et al., 2004); metabolism modifiers (Quiniou et al., 1993; Caperna et al., 1995); antibiotics (Roth and Kirchgessner, 1993a,b); changes in immune status (Williams et al., 1997); and proper feeder adjustment to reduce wastage.

As the intensity of swine production increases over a given amount of land mass, the distribution of manure has also to be balanced with agronomic needs to prevent surface or groundwater contamination and minimize the accumulation of minerals in the soil. Excess nitrogen application can lead to increases in nitrogen runoff in surface water and nitrate content of groundwater. Excess phosphorus application results in excess buildup of phosphorus in the soil, and although phosphorus is adsorbed onto soil particles and does not leach into groundwater, it can erode (along with soil particles) into streams, lakes, and rivers where it is the most limiting nutrient that regulates aquatic plant growth (Pierzynski et al., 1994; Sharpley et al., 1994), leading to a general deterioration of water quality (Crenshaw and Johanson, 1995). Combined with minimization of nutrient excretion, a goal of swine production is to link manure composition, either from tabular (ASAE, 2005) or analyzed composition, with manure storage effects (Petersen et al., 1998) and application methods (Hoff et al., 1981) to agronomic needs.

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15

Research Needs

INTRODUCTION

The statement of task for the 11th revised edition of the *Nutrient Requirements of Swine* includes the sentence "Future areas of needed research will be identified." This chapter addresses that important task. Reviews of the literature identified areas that lacked or were devoid of information. Much needs to be done in the area of swine nutrition as it relates to the type of pig used today. Similarly, more information is needed on feed ingredient composition. However, some of the voids of information are much more economically important than others to optimize efficiency of swine production.

METHODS OF NUTRIENT REQUIREMENT ASSESSMENT

It is important that experiments to determine nutrient requirements contain information about the available nutrient contents in experimental diets, that the main determinants of nutrient requirements be characterized, and that standardized research methodologies and laboratory procedures be used. It is helpful if studies in which pig performance is measured are complemented with metabolism studies in which key aspects of nutrient utilization are quantified. The latter will allow further development of models to predict the animal's response to varying nutrient intakes and generate estimates of nutrient requirements for specific groups of swine. Further development of such models will involve careful testing of model-generated requirements against empirically determined nutrient requirements that have been conducted under clearly defined conditions.

A key determinant of optimum nutrient levels in diets for groups of swine is "among-animal" variability. Therefore, attempts should be made to quantify among-animal variability when conducting nutrient requirement studies. In addition, the influence of dietary nutrient levels on observed among-animal variability in performance is an important element.

NUTRIENT UTILIZATION AND FEED INTAKE

The efficiency of nitrogen/amino acid utilization for the whole body and for edible products, the efficiency of using digestible nutrient and energy intake for the key body functions (e.g., body protein and lipid gain, nutrient output in milk), and estimation of nutrient losses associated with body maintenance functions (e.g., amino acid catabolism that is associated with body protein turnover and contributes minimum urinary N losses) need additional data. The impact of dietary (e.g., dietary levels of fermentable fiber and antinutritional factors and feed processing) and animal factors (e.g., stage of development, pig genotype, health status, and stress) and metabolic modifiers (immunocastration and β-agonists) on nutrient utilization need further research as there is insufficient information on how they affect postabsorptive efficiency of nutrient and energy for various body functions.

Quantitative information is needed to relate chemical body composition (e.g., body mass of protein, lipid, water, ash, calcium, and phosphorus) to physical body composition (e.g., visceral organ and edible muscle mass) in order to optimize protein and lipid gain in edible pork products and to quantify nutrient losses into the environment. Furthermore, the impact of nutrient intake during early stages of growth on subsequent nutrient utilization, growth, and body composition needs to be addressed.

The interactive effects of nutrient intake during gestation, lactation, and early stages of growth on reproductive performance are important. In lactating sows, a better understanding of postabsorptive nutrient utilization is required to understand the impact of energy, amino acid, and mineral intakes on milk production and composition, and their relationship to retention or mobilization of body stores. These factors also need to be addressed relative to differences across parities, genotypes, and initial body composition.

Continued research is needed to permit accurate prediction of feed intake of pigs as affected by interactions among pig genotype, health status, diet composition, and environment factors (e.g., thermal, physical).

ENERGY

In most energy systems, net energy (NE) values are predicted from either empirical digestible energy (DE) or metabolizable energy (ME) values, from total tract nutrient digestibility coefficients (e.g., DM, N, EE, and NFE), or from the ingredient's nutrient composition. In the current feed database, however, insufficient recent information is available on the nutrient content, total tract nutrient digestibility coefficients, or empirical energy values for many ingredients. Consequently, priority needs to be placed on assembling the chemical composition of feedstuffs, determining (bio)availability of nutrients, which may be estimated from ileal and total tract energy and nutrient digestibility, and the development of standardized or reference procedures to estimate their NE content, and subsequent validation with growth performance and body composition indexes. In addition, composition, digestibility, and energy values for various lipid sources, the impact of form (e.g., intracellular versus extracted) on their energy digestibility, and the impact of dietary composition on true lipid digestibility have not been adequately evaluated. Consequently, future research needs to consider all of these factors to advance the understanding of energy digestibility and utilization, and to further the understanding of energy metabolism. In addition, models describing energy utilization to replace existing energy-based (e.g., ME and NE) systems may have the advantage of evaluating evolving and nontraditional feedstuffs (e.g., wet- and dry-milling coproducts) for various body functions more effectively than existing energy prediction equations. This is because of the extreme nutrient content (i.e., outside the range of nutrient profiles used to parameterize DE/ME/NE prediction regression equations) of these feedstuffs.

Expressions of energy utilization components are considered single unique values; however, variation exists in terms of the specific components (e.g., maintenance, efficiency of energy use for lipid and protein deposition) as applied to populations of pigs that are independent of diet composition and cannot be accounted for relative to current prediction approaches (models). In future research it will be helpful to consider mechanistically defining variation in maintenance energy needs and developing the appropriate predictive equations.

Identifying relationships between energy intake and protein/lipid deposition in growing-finishing pigs, conceptus/maternal tissue accretion/mobilization in gestating sows, and milk production/milk composition/litter performance in lactating sows with various physiological capacities (genetic potentials) need to be explored to improve understanding of energy requirement estimates and modeled responses. Lastly, little data exist describing the effect of immunocastration or exogenous growth promotants on energy intake and utilization for maintenance and growth.

AMINO ACIDS

There is more research into amino acid requirements for all categories of swine than for any other class of nutrient. The lysine requirement is reasonably defined; however, certain other information is lacking. Research is needed to determine the digestible tryptophan, threonine, valine, isoleucine, and methionine requirements for body weight and protein gain. More information is needed about the factors (e.g., pig health status and dietary fermentable fiber content) that impact requirements for specific amino acids (such as cysteine, tryptophan, and threonine) that are used for immune and other nonproduction functions. Also, the requirements for nitrogen—for synthesis of nonessential amino acids—need further exploration, in particular when an increasing number of amino acids are added to swine diets in crystalline form.

In gestation, there is a need for additional requirement estimates for lysine, threonine, tryptophan, methionine, and arginine; amino acid profiles for the various body protein pools during the last trimester of gestation; gestation body weight changes; direct estimates of efficiency of amino acid utilization into N retention from early (day 30) through late (day 110) gestation; and the amino acid profile of mammary, fetal, placental, and uterine tissue and of maternal body protein gain at distinct phases of gestation. This information is necessary to model requirements for all essential amino acids, conditionally essential amino acids, and total N.

During lactation, there is a need for more estimates of amino acid utilization efficiency into milk protein and of milk protein into litter gain. Requirement estimates for lysine, threonine, methionine, tryptophan, valine, and isoleucine are also needed.

There are very few estimates of the amino acid (and all other nutrient) requirements of the mature or developing boar, and relevant response criteria remain to be determined that are reflective of the boar's activities.

MINERALS

It is important to determine the rates of whole-body Ca and P retention and relate them to response variables, such as body protein deposition or another key physiological response. Because of the change in genetics, diets, and feedstuffs relative to previous Ca and P requirement experimentation, the Ca and P requirements of all categories of growing pigs for growth and bone strength need to be reevaluated. Similar data for gilts and sows need to be determined relative to gilt development, sow productivity, and sow longevity.

Electrolyte balance and the requirement for Na and Cl need to be reevaluated, particularly in finisher pigs with emphasis on different feedstuffs (of differing fiber type and content) and phytase supplementation. Water utilization in agriculture will become more important and excess dietary NaCl affects water intake and excretion, but these two minerals clearly affect nutrient digestibility as evidenced by the nursery and early grower research.

Zinc is the mineral most likely to be deficient in swine diets after Ca, P, Na, and Cl, and the need for Zn is related to protein synthesis. With the increasing amount of muscle in the finishing pig, the need for Zn throughout the life cycle is an important trait to reevaluate.

Phytase is one of the most studied enzymes and its dietary addition affects utilization of several minerals other than P. Phytase addition may also affect energy utilization when supplemented at higher levels than currently utilized, but data are lacking in these areas of swine nutrition.

LIPIDS

The gross nutritional attributes of dietary lipids are well understood, and utilization throughout the life cycle has been reasonably well characterized. Research with lipids in swine diets has increased during the last decade because of the advancements in understanding of active lipids and the availability of agricultural coproducts with high fat concentrations. However, research with lipids is needed to determine the standardized ileal digestibility of fat sources in pigs, especially nursery pigs; the NE value of fat sources for all categories of swine; the usefulness of antioxidants as feed additives; the role n-6 and n-3 bioactive fatty acids play in pig and sow health and reproduction; the effects of fat quality on its feeding value, pig health, and pork quality; and the feeding value of fat for lactating sows under summer heat stress. Because of the availability of oils with high concentrations of polyunsaturated fatty acids, the equations to predict carcass iodine value and dietary iodine value product need to be redefined.

VITAMINS

Much of the research on vitamins is dated or cannot be used to revise requirement estimates from previous revisions because the experiments were designed to answer qualitative questions (i.e., is there a response to a higher level) rather than quantitative questions (i.e., what is the requirement based on a dose-titration design). The most glaring vitamin research needs are in the area of sow reproduction, and it is important to focus more on lifetime nutrition (minimum of two parities, preferably up to four parities) as it affects aspects of production, health, and well-being rather than litter size and weight in a single-parity study. Specifically, in the area of sow research, improvements in bone health from vitamin D supplementation indicate that this vitamin may play an integral role in levels of Ca and P that are needed to optimize sow longevity; consequently, more work to refine the appropriate supplementation levels is necessary. There has never been a vitamin K study with reproducing sows reported, nor is there adequate information on the potential niacin, pantothenic acid, or thiamin needs for reproduction. Additionally, research in sows on vitamins B_6 and B_{12} has shown promise but much more needs to be done to validate when they are needed and at what supplementation level.

FEED INGREDIENT COMPOSITION

For this edition of the *Nutrient Requirements of Swine*, the literature was reviewed over the last 10 to 20 years to completely revise with new information the composition of feed ingredients. Each of the 122 ingredient sheets contains 130 nutrients or proximate component data points including the digestibility of some of those nutrient/components. Of these 122 ingredients, few had adequate published data to complete the proximate and nutrient component profile, digestibility, and bioavailability.

The missing information is more economically important for some nutrients than others. For example, there are no data on the vitamin composition of many of the agricultural coproducts and few recent vitamin composition data are available on any ingredient, but most, if not all, nutritionists add a vitamin mix to swine diets that more than meets the vitamin requirements of pigs. Thus, because of the cost of each vitamin analysis and the product of the number of ingredients by the number of vitamins, the cost-return of analyzing ingredients for vitamins may be very ineffective.

Initially, it will be desirable to place emphasis on economically important nutrients and their standardized or apparent ileal or total tract digestibility or bioavailability. It will be helpful to collect data on the value and variation in the standardized ileal digestibility of amino acids, the standardized total tract digestibility of P, and the apparent total tract digestibility of Ca in commonly used ingredients that lack those data.

OTHER AREAS AND PRIORITIES

Research needs to be conducted to improve understanding of the impact of dietary N, S, and fiber (sources and levels) on ammonia, volatile fatty acid, and greenhouse gas emissions, including measures of odor. Data need to be developed to describe how and when carbohydrase enzyme cocktails improve carbohydrate digestibility (and subsequent energy digestibility) relative to dietary complex carbohydrates. Information on the impact of feed additives on gastrointestinal health and subsequent pig productivity are lacking, as is an understanding of the impact of gastrointestinal microbiology on whole-animal productivity, not just site-specific intestinal or immunological specific responses. Research needs to be conducted to determine the interactive effects between feed processing, particle size, and enzyme cocktails.

Although a review of this chapter makes it seem as if little is known about the nutrient needs of the pig, in fact, more is known about the nutritional needs of the pig than of any other livestock species. Unlimited resources would permit the conduct of most of the research outlined in this chapter. However, with more limited resources, research ought to be focused on the amino acid, Ca, and P requirements of all categories of pigs, with the greatest emphasis on the sow.

Nutrient Requirements, Feed Composition, and Other Tables

16

Nutrient Requirements Tables

INTRODUCTION

Nutrient requirements of starting, growing, and finishing pigs; gestating and lactating sows; and sexually active boars are provided in the tables of this chapter. All nutrient requirements relate to swine that are managed in a relatively stress-free environment, in terms of environmental temperature, exposure to disease-causing organisms, and space allowance. Estimates are listed for energy, amino acids, nitrogen, minerals, vitamins, and linoleic acid. The amino acid and nitrogen requirements are expressed on a standardized ileal digestible and apparent ileal digestible basis; these values apply to all types of feed ingredients. Amino acid and nitrogen requirements are also expressed on a total basis, which applies to corn-soybean meal–based diets. Similarly, for phosphorus, requirements are listed on a standardized total tract digestible, apparent total tract digestible, and total basis. For all nutrients the requirements include the amounts of these nutrients that are provided by feed ingredients.

For growing-finishing pigs (25 to 135 kg body weight), gestating sows, and lactating sows, all requirements for amino acids, nitrogen, calcium, and phosphorus are generated by the models described in Chapter 8. Lysine requirements of weanling pigs (5 to 25 kg body weight) are derived from empirical requirement studies, and a modeling approach was used to estimate requirements for other amino acids and nitrogen, as described in Chapter 8. For all other nutrients, requirements are derived from empirical nutrient requirement studies and are the committee's best estimates of the dietary requirements for average pigs.

Tables 16-1 to 16-4 give estimated requirements of young weanling pigs from 5 to 25 kg and of growing-finishing pigs from 25 to 135 kg body weight. The amino acid requirements in Table 16-1 are for pigs (equal ratio of barrows and gilts) of a high-medium lean growth rate (mean whole-body protein deposition of 135 g/day from 25 to 125 kg). Table 16-2 gives separate requirements for barrows, gilts, and boars with high-medium lean growth rates from 50 to 75, 75 to 100, and 100 to 135 kg. Table 16-3 provides requirements of pigs (equal ratio of barrows and gilts) with three different mean whole-body protein depositions (115, 135, and 155 g/day), and Table 16-4 gives requirements of entire males immunized against gonadotrophin releasing hormone or fed ractopamine, and barrows and gilts fed ractopamine. Calcium and phosphorus (standardized total tract digestible, apparent total tract digestible, and total) requirements are also presented in Tables 16-1 to 16-4. Requirements for other minerals, vitamins, and linoleic acid are given in Table 16-5.

Tables 16-6 and 16-7 provide amino acid requirements of gestating sows of various breeding weights, gestation weight gains, and anticipated litter sizes and for lactating sows of various postfarrowing weights, lactation weight changes, and weight gains of their pigs. Dietary concentrations and daily intake requirements of minerals, vitamins, and linoleic acid are given in Table 16-8. Table 16-9 lists estimated requirements of sexually active boars.

The amino acid, nitrogen, calcium, and phosphorus requirements in the tables are given as examples. The models included in this publication allow the user to generate tables of estimates of requirements for these nutrients for swine under various conditions (e.g., different lean growth rates, feed intakes, energy density of diets, environmental temperature, or floor space). The models may generate slightly different estimates of mineral and vitamin requirements of weanling pigs and growing-finishing pigs because they use an exponential equation to estimate the requirements at various body weights; for similar reasons, model-generated estimates of amino acid requirements of weanling pigs may differ slightly from the values that are reported in the tables.

The requirements for certain minerals and/or vitamins by pigs possessing a high lean growth rate, because of superior genetics or high health status, may be higher than the levels shown in the tables, but definitive information was not available to estimate a higher quantitative requirement. Approximately 15% higher levels of calcium and phosphorus than shown in the tables are required by developing boars and replacement gilts from 50 to 135 kg body weight (Chapter 7).

The requirements listed in the following tables do not include any intentional surpluses. They are the committee's best estimates of minimum requirements. In practice, however, a margin of safety is commonly added to the stated requirements, and these levels are often referred to as nutrient "allowances." Nutrient allowances are generally established by professional nutritionists to account for variability in nutrient composition and in nutrient bioavailability of feedstuffs, presence of inhibitors or toxins in ingredients, inadequate processing or mixing of diets, partial loss of nutrients from storage, and other factors. For example, contents and bioavailabilities of trace minerals and vitamins in feed ingredients can be highly variable and are often not analyzed. Levels of supplementation of trace minerals or vitamins may be at or above estimated requirements and any amounts supplied by feed ingredients then contribute to the margin of safety. Because of these factors, the statement on a feed label that the product "meets or exceeds National Research Council requirements" by itself is not necessarily evidence of a complete and balanced diet. Knowledge of the nutritional constraints and limitations is important for the proper use of the requirement tables that follow.

TABLE 16-1A Dietary Calcium, Phosphorus, and Amino Acid Requirements of Growing Pigs When Allowed Feed Ad Libitum (90% dry matter)[a]

	Body Weight Range (kg)						
Item	5-7	7-11	11-25	25-50	50-75	75-100	100-135
NE content of the diet (kcal/kg)[b]	2,448	2,448	2,412	2,475	2,475	2,475	2,475
Effective DE content of diet (kcal/kg)[b]	3,542	3,542	3,490	3,402	3,402	3,402	3,402
Effective ME content of diet (kcal/kg)[b]	3,400	3,400	3,350	3,300	3,300	3,300	3,300
Estimated effective ME intake (kcal/day)	904	1,592	3,033	4,959	6,989	8,265	9,196
Estimated feed intake + wastage (g/day)[c]	280	493	953	1,582	2,229	2,636	2,933
Body weight gain (g/day)	210	335	585	758	900	917	867
Body protein deposition (g/day)	—	—	—	128	147	141	122
	Calcium and phosphorus (%)						
Total calcium	0.85	0.80	0.70	0.66	0.59	0.52	0.46
STTD phosphorus[d]	0.45	0.40	0.33	0.31	0.27	0.24	0.21
ATTD phosphorus[e,f]	0.41	0.36	0.29	0.26	0.23	0.21	0.18
Total phosphorus[f]	0.70	0.65	0.60	0.56	0.52	0.47	0.43
	Amino acids[g,h]						
	Standardized ileal digestible basis (%)						
Arginine	0.68	0.61	0.56	0.45	0.39	0.33	0.28
Histidine	0.52	0.46	0.42	0.34	0.29	0.25	0.21
Isoleucine	0.77	0.69	0.63	0.51	0.45	0.39	0.33
Leucine	1.50	1.35	1.23	0.99	0.85	0.74	0.62
Lysine	**1.50**	**1.35**	**1.23**	**0.98**	**0.85**	**0.73**	**0.61**
Methionine	0.43	0.39	0.36	0.28	0.24	0.21	0.18
Methionine + cysteine	0.82	0.74	0.68	0.55	0.48	0.42	0.36
Phenylalanine	0.88	0.79	0.72	0.59	0.51	0.44	0.37
Phenylalanine + tyrosine	1.38	1.25	1.14	0.92	0.80	0.69	0.58
Threonine	0.88	0.79	0.73	0.59	0.52	0.46	0.40
Tryptophan	0.25	0.22	0.20	0.17	0.15	0.13	0.11
Valine	0.95	0.86	0.78	0.64	0.55	0.48	0.41
Total nitrogen	3.10	2.80	2.56	2.11	1.84	1.61	1.37
	Apparent ileal digestible basis (%)						
Arginine	0.64	0.57	0.51	0.41	0.34	0.29	0.24
Histidine	0.49	0.44	0.40	0.32	0.27	0.24	0.19
Isoleucine	0.74	0.66	0.60	0.49	0.42	0.36	0.30
Leucine	1.45	1.30	1.18	0.94	0.81	0.69	0.57
Lysine	**1.45**	**1.31**	**1.19**	**0.94**	**0.81**	**0.69**	**0.57**
Methionine	0.42	0.38	0.34	0.27	0.23	0.20	0.16
Methionine + cysteine	0.79	0.71	0.65	0.53	0.46	0.40	0.33
Phenylalanine	0.85	0.76	0.69	0.56	0.48	0.41	0.34
Phenylalanine + tyrosine	1.32	1.19	1.08	0.87	0.75	0.65	0.54
Threonine	0.81	0.73	0.67	0.54	0.47	0.41	0.35
Tryptophan	0.23	0.21	0.19	0.16	0.13	0.12	0.10
Valine	0.89	0.80	0.73	0.59	0.51	0.44	0.36
Total nitrogen	2.84	2.55	2.32	1.88	1.62	1.40	1.16

TABLE 16-1A Continued

Item	Body Weight Range (kg)						
	5-7	7-11	11-25	25-50	50-75	75-100	100-135
				Total basis (%)			
Arginine	0.75	0.68	0.62	0.50	0.44	0.38	0.32
Histidine	0.58	0.53	0.48	0.39	0.34	0.30	0.25
Isoleucine	0.88	0.79	0.73	0.59	0.52	0.45	0.39
Leucine	1.71	1.54	1.41	1.13	0.98	0.85	0.71
Lysine	**1.70**	**1.53**	**1.40**	**1.12**	**0.97**	**0.84**	**0.71**
Methionine	0.49	0.44	0.40	0.32	0.28	0.25	0.21
Methionine + cysteine	0.96	0.87	0.79	0.65	0.57	0.50	0.43
Phenylalanine	1.01	0.91	0.83	0.68	0.59	0.51	0.43
Phenylalanine + tyrosine	1.60	1.44	1.32	1.08	0.94	0.82	0.70
Threonine	1.05	0.95	0.87	0.72	0.64	0.56	0.49
Tryptophan	0.28	0.25	0.23	0.19	0.17	0.15	0.13
Valine	1.10	1.00	0.91	0.75	0.65	0.57	0.49
Total nitrogen	3.63	3.29	3.02	2.51	2.20	1.94	1.67

[a]Mixed gender (1:1 ratio of barrows to gilts) of pigs with high-medium lean growth rate (mean whole body-protein deposition of 135 g/day) from 25 to 125 kg body weight.

[b]Dietary energy contents relate to corn and soybean meal–based diets. Effective DE and effective ME contents are calculated from NE contents using fixed conversion values for pigs below and above 25 kg body weight. For corn and soybean meal–based diets, effective DE and effective ME contents are similar to actual DE and ME contents. The optimum dietary energy content varies with availability and costs of local feed ingredients. When using alternative feed ingredients, it is suggested that diets be formulated based on NE contents and nutrient requirements be adjusted to maintain constant nutrient-to-net energy ratios.

[c]Assumes 5% feed wastage.

[d]Standardized total tract digestible.

[e]Apparent total tract digestible.

[f]Apparent total tract digestible and total phosphorus requirements apply to corn and soybean meal–based diets only and have been calculated from standardized total tract digestible phosphorus requirements and nutrient profiles in corn, dehulled solvent-extracted soybean meal, and dicalcium phosphate. Diets were assumed to contain 0.1% added lysine·HCl and 3% added vitamins and minerals. Corn and soybean meal levels were calculated to meet standardized ileal digestible lysine requirements, and dicalcium phosphate amounts were varied to meet requirements for standardized total tract digestible phosphorus.

[g]Lysine percentages for 5- to 25-kg pigs are estimated from empirical data. The other amino acids for 5- to 25-kg pigs are based on the ratios of amino acids to lysine based on amino acid requirements for maintenance and growth. The requirements for 25- to 135-kg pigs are estimated from the growth model.

[h]Apparent ileal digestible and total amino acid requirements apply to corn and soybean meal–based diets only and have been calculated from standardized ileal digestible amino acid requirements and amino acid contents in corn and dehulled solvent-extracted soybean meal–based diets with 0.1% added lysine·HCl and containing 3% added vitamins and minerals. For each amino acid, dietary levels of corn and soybean meal levels and nutrient requirements were calculated to meet standardized ileal digestible requirements.

TABLE 16-1B Daily Calcium, Phosphorus, and Amino Acid Requirements of Growing Pigs When Allowed Feed Ad Libitum (90% dry matter)[a]

	Body Weight Range (kg)						
Item	5-7	7-11	11-25	25-50	50-75	75-100	100-135
NE content of the diet (kcal/kg)[b]	2,448	2,448	2,412	2,475	2,475	2,475	2,475
Effective DE content of diet (kcal/kg)[b]	3,542	3,542	3,490	3,402	3,402	3,402	3,402
Effective ME content of diet (kcal/kg)[b]	3,400	3,400	3,350	3,300	3,300	3,300	3,300
Estimated effective ME intake (kcal/day)	904	1,592	3,033	4,959	6,989	8,265	9,196
Estimated feed intake + wastage (g/day)[c]	280	493	953	1,582	2,229	2,636	2,933
Body weight gain (g/day)	210	335	585	758	900	917	867
Body protein deposition (g/day)	—	—	—	128	147	141	122
	Calcium and phosphorus (g/day)						
Total calcium	2.26	3.75	6.34	9.87	12.43	13.14	12.80
STTD phosphorus[d]	1.20	1.87	2.99	4.59	5.78	6.11	5.95
ATTD phosphorus[e,f]	1.09	1.69	2.63	3.90	4.89	5.15	4.98
Total phosphorus[f]	1.86	3.04	5.43	8.47	10.92	11.86	11.97
	Amino acids[g,h]						
	Standardized ileal digestible basis (g/day)						
Arginine	1.8	2.9	5.1	6.8	8.2	8.4	7.8
Histidine	1.4	2.2	3.8	5.1	6.2	6.3	5.8
Isoleucine	2.0	3.2	5.7	7.7	9.4	9.7	9.1
Leucine	4.0	6.3	11.1	14.9	18.1	18.5	17.2
Lysine	**4.0**	**6.3**	**11.1**	**14.8**	**17.9**	**18.3**	**16.9**
Methionine	1.2	1.8	3.2	4.3	5.2	5.3	4.9
Methionine + cysteine	2.2	3.5	6.1	8.3	10.2	10.5	9.9
Phenylalanine	2.3	3.7	6.6	8.8	10.8	11.0	10.3
Phenylalanine + tyrosine	3.7	5.8	10.3	13.8	16.9	17.3	16.3
Threonine	2.3	3.7	6.6	8.9	11.1	11.6	11.1
Tryptophan	0.7	1.0	1.8	2.5	3.1	3.2	3.0
Valine	2.5	4.0	7.1	9.6	11.7	12.1	11.4
Total nitrogen	8.3	13.1	23.2	31.7	39.0	40.2	38.1
	Apparent ileal digestible basis (g/day)						
Arginine	1.7	2.7	4.7	6.1	7.3	7.3	6.6
Histidine	1.3	2.1	3.6	4.8	5.8	5.9	5.4
Isoleucine	2.0	3.1	5.5	7.3	8.9	9.0	8.4
Leucine	3.8	6.1	10.7	14.1	17.1	17.3	16.0
Lysine	**3.9**	**6.1**	**10.7**	**14.1**	**17.1**	**17.3**	**15.9**
Methionine	1.1	1.8	3.1	4.1	4.9	5.0	4.6
Methionine + cysteine	2.1	3.3	5.9	7.9	9.7	9.9	9.3
Phenylalanine	2.3	3.6	6.3	8.4	10.1	10.3	9.6
Phenylalanine + tyrosine	3.5	5.6	9.8	13.1	15.9	16.3	15.1
Threonine	2.2	3.4	6.0	8.1	9.9	10.3	9.7
Tryptophan	0.6	1.0	1.7	2.3	2.8	2.9	2.7
Valine	2.4	3.7	6.6	8.8	10.7	10.9	10.2
Total nitrogen	7.6	12.0	21.0	28.3	34.3	35.0	32.5

TABLE 16-1B Continued

Item	Body Weight Range (kg)						
	5-7	7-11	11-25	25-50	50-75	75-100	100-135
	Total basis (g/day)						
Arginine	2.0	3.2	5.6	7.6	9.3	9.6	9.0
Histidine	1.6	2.5	4.4	5.9	7.2	7.4	7.0
Isoleucine	2.3	3.7	6.6	8.9	11.0	11.4	10.8
Leucine	4.6	7.2	12.7	17.0	20.8	21.3	19.9
Lysine	**4.5**	**7.2**	**12.6**	**16.9**	**20.6**	**21.1**	**19.7**
Methionine	1.3	2.1	3.6	4.9	6.0	6.1	5.8
Methionine + cysteine	2.5	4.1	7.2	9.8	12.1	12.6	12.0
Phenylalanine	2.7	4.3	7.5	10.2	12.5	12.8	12.1
Phenylalanine + tyrosine	4.2	6.8	12.0	16.2	20.0	20.6	19.5
Threonine	2.8	4.4	7.9	10.8	13.4	14.1	13.7
Tryptophan	0.7	1.2	2.1	2.9	3.5	3.7	3.5
Valine	2.9	4.7	8.3	11.3	13.9	14.4	13.6
Total nitrogen	9.7	15.4	27.3	37.7	46.6	48.6	46.5

[a]Mixed gender (1:1 ratio of barrows to gilts) of pigs with high-medium lean growth rate (mean whole-body protein deposition of 135 g/day) from 25 to 125 kg body weight.

[b]Dietary energy contents relate to corn and soybean meal–based diets. Effective DE and effective ME contents are calculated from NE contents using fixed conversion values for pigs below and above 25 kg body weight. For corn and soybean meal–based diets, effective DE and effective ME contents are similar to actual DE and ME contents. The optimum dietary energy content varies with availability and costs of local feed ingredients. When using alternative feed ingredients, it is suggested that diets be formulated based on NE contents and nutrient requirements be adjusted to maintain constant nutrient-to-net energy ratios.

[c]Assumes 5% feed wastage.

[d]Standardized total tract digestible.

[e]Apparent total tract digestible.

[f]Apparent total tract digestible and total phosphorus requirements apply to corn and soybean meal–based diets only and have been calculated from standardized total tract digestible phosphorus requirements and nutrient profiles in corn, dehulled solvent-extracted soybean meal, and dicalcium phosphate. Diets were assumed to contain 0.1% added lysine·HCl and 3% added vitamins and minerals. Corn and soybean meal levels were calculated to meet standardized ileal digestible lysine requirements, and dicalcium phosphate amounts were varied to meet requirements for standardized total tract digestible phosphorus.

[g]Lysine percentages for 5- to 25-kg pigs are estimated from empirical data. The other amino acids for 5- to 25-kg pigs are based on the ratios of amino acids to lysine based on amino acid requirements for maintenance and growth. The requirements for 25- to 135-kg pigs are estimated from the growth model.

[h]Apparent ileal digestible and total amino acid requirements apply to corn and soybean meal–based diets only and have been calculated from standardized ileal digestible amino acid requirements and amino acid contents in corn and dehulled solvent-extracted soybean meal–based diets with 0.1% added lysine·HCl and containing 3% added vitamins and minerals. For each amino acid, dietary levels of corn and soybean meal levels and nutrient requirements were calculated to meet standardized ileal digestible requirements.

TABLE 16-2A Dietary Calcium, Phosphorus, and Amino Acid Requirements of Barrows, Gilts, and Entire Males of Different Weights When Allowed Feed Ad Libitum (90% dry matter)

Body Weight Range (kg)	50 to 75			75 to 100			100 to 135		
Gender	Barrows	Gilts	Entire Males	Barrows	Gilts	Entire Males	Barrows	Gilts	Entire Males
NE content of the diet (kcal/kg)[a]	2,475	2,475	2,475	2,475	2,475	2,475	2,475	2,475	2,475
Effective DE content of diet (kcal/kg)[a]	3,402	3,402	3,402	3,402	3,402	3,402	3,402	3,402	3,402
Effective ME content of diet (kcal/kg)[a]	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300
Estimated effective ME intake (kcal/day)	7,282	6,658	6,466	8,603	7,913	7,657	9,495	8,910	8,633
Estimated feed intake + wastage (g/day)[b]	2,323	2,124	2,062	2,744	2,524	2,442	3,029	2,842	2,754
Body weight gain (g/day)	917	866	872	936	897	922	879	853	906
Body protein deposition (g/day)	145	145	150	139	144	156	119	126	148
				Calcium and phosphorus (%)					
Total calcium	0.56	0.61	0.64	0.50	0.56	0.61	0.43	0.49	0.57
STTD phosphorus[c]	0.26	0.28	0.30	0.23	0.26	0.29	0.20	0.23	0.27
ATTD phosphorus[d,e]	0.22	0.24	0.25	0.19	0.22	0.24	0.17	0.19	0.23
Total phosphorus[e]	0.50	0.53	0.55	0.45	0.49	0.53	0.41	0.45	0.50
				Amino acids[f,g]					
				Standardized ileal digestible basis (%)					
Arginine	0.37	0.40	0.40	0.32	0.35	0.37	0.27	0.29	0.33
Histidine	0.28	0.30	0.30	0.24	0.26	0.28	0.20	0.22	0.25
Isoleucine	0.43	0.46	0.46	0.37	0.41	0.43	0.31	0.34	0.39
Leucine	0.82	0.88	0.89	0.70	0.78	0.83	0.59	0.65	0.74
Lysine	**0.81**	**0.87**	**0.88**	**0.69**	**0.77**	**0.82**	**0.58**	**0.64**	**0.73**
Methionine	0.23	0.25	0.26	0.20	0.22	0.24	0.17	0.18	0.21
Methionine + cysteine	0.46	0.49	0.50	0.40	0.44	0.47	0.34	0.37	0.42
Phenylalanine	0.49	0.52	0.53	0.42	0.46	0.49	0.35	0.39	0.44
Phenylalanine + tyrosine	0.76	0.82	0.83	0.66	0.73	0.77	0.56	0.61	0.69
Threonine	0.50	0.53	0.54	0.44	0.48	0.51	0.38	0.42	0.46
Tryptophan	0.14	0.15	0.15	0.12	0.13	0.14	0.10	0.11	0.13
Valine	0.53	0.57	0.58	0.46	0.51	0.54	0.39	0.43	0.48
Total nitrogen	1.76	1.88	1.91	1.54	1.69	1.78	1.31	1.43	1.61
				Apparent ileal digestible basis (%)					
Arginine	0.33	0.35	0.36	0.28	0.31	0.33	0.22	0.25	0.29
Histidine	0.26	0.28	0.29	0.22	0.25	0.26	0.18	0.20	0.24
Isoleucine	0.40	0.43	0.44	0.34	0.38	0.40	0.29	0.32	0.36
Leucine	0.77	0.83	0.84	0.66	0.73	0.78	0.54	0.60	0.70
Lysine	**0.77**	**0.83**	**0.84**	**0.65**	**0.73**	**0.78**	**0.54**	**0.60**	**0.69**
Methionine	0.22	0.24	0.24	0.19	0.21	0.22	0.16	0.17	0.20
Methionine + cysteine	0.44	0.47	0.47	0.38	0.42	0.44	0.32	0.35	0.40
Phenylalanine	0.46	0.49	0.50	0.39	0.44	0.46	0.33	0.36	0.41
Phenylalanine + tyrosine	0.72	0.77	0.78	0.62	0.68	0.73	0.52	0.57	0.65
Threonine	0.45	0.48	0.49	0.39	0.43	0.45	0.33	0.36	0.41
Tryptophan	0.13	0.14	0.14	0.11	0.12	0.13	0.09	0.10	0.12
Valine	0.48	0.52	0.53	0.42	0.46	0.49	0.35	0.38	0.44
Total nitrogen	1.55	1.66	1.69	1.33	1.47	1.56	1.11	1.22	1.40

TABLE 16-2A Continued

Body Weight Range (kg)	50 to 75			75 to 100			100 to 135		
Gender	Barrows	Gilts	Entire Males	Barrows	Gilts	Entire Males	Barrows	Gilts	Entire Males
					Total basis (%)				
Arginine	0.42	0.45	0.46	0.37	0.40	0.42	0.31	0.34	0.38
Histidine	0.32	0.35	0.35	0.28	0.31	0.33	0.24	0.26	0.30
Isoleucine	0.50	0.53	0.54	0.43	0.48	0.50	0.37	0.40	0.45
Leucine	0.94	1.00	1.02	0.81	0.89	0.95	0.68	0.75	0.85
Lysine	**0.93**	**0.99**	**1.01**	**0.80**	**0.89**	**0.94**	**0.67**	**0.74**	**0.85**
Methionine	0.27	0.29	0.29	0.23	0.26	0.27	0.20	0.22	0.25
Methionine + cysteine	0.55	0.58	0.59	0.48	0.53	0.55	0.41	0.45	0.50
Phenylalanine	0.56	0.60	0.61	0.49	0.54	0.57	0.41	0.45	0.51
Phenylalanine + tyrosine	0.90	0.96	0.98	0.79	0.86	0.91	0.67	0.73	0.83
Threonine	0.61	0.65	0.66	0.54	0.59	0.62	0.47	0.51	0.56
Tryptophan	0.16	0.17	0.17	0.14	0.15	0.16	0.12	0.13	0.15
Valine	0.63	0.67	0.68	0.55	0.60	0.63	0.47	0.51	0.57
Total nitrogen	2.12	2.25	2.28	1.86	2.03	2.13	1.60	1.74	1.94

[a]Dietary energy contents relate to corn and soybean meal–based diets. Effective DE and effective ME contents are calculated from NE contents using fixed conversion values for pigs above 25 kg body weight. For corn and soybean meal–based diets, effective DE and effective ME contents are similar to actual DE and ME contents. The optimum dietary energy content varies with availability and costs of local feed ingredients. When using alternative feed ingredients, it is suggested that diets be formulated based on NE contents and nutrient requirements be adjusted to maintain constant nutrient-to-net energy ratios.

[b]Assumes 5% feed wastage.

[c]Standardized total tract digestible.

[d]Apparent total tract digestible.

[e]Apparent total tract digestible and total phosphorus requirements apply to corn and soybean meal–based diets only and have been calculated from standardized total tract digestible phosphorus requirements and nutrient profiles in corn, dehulled solvent-extracted soybean meal and dicalcium phosphate. Diets were assumed to contain 0.1% added lysine·HCl and 3% added vitamins and minerals. Corn and soybean meal levels were calculated to meet standardized ileal digestible lysine requirements, and dicalcium phosphate amounts were varied to meet requirements for standardized total tract digestible phosphorus.

[f]The requirements are estimated from the growth model.

[g]Apparent ileal digestible and total amino acid requirements apply to corn and soybean meal–based diets only and have been calculated from standardized ileal digestible amino acid requirements and amino acid contents in corn and dehulled solvent-extracted soybean meal–based diets with 0.1% added lysine·HCl and containing 3% added vitamins and minerals. For each amino acid, dietary levels of corn and soybean meal levels and nutrient requirements were calculated to meet standardized ileal digestible requirements.

TABLE 16-2B Daily Calcium, Phosphorus, and Amino Acid Requirements of Barrows, Gilts, and Entire Males of Different Weights When Allowed Feed Ad Libitum (90% dry matter)

Body Weight Range (kg)	50 to 75			75 to 100			100 to 135		
Gender	Barrows	Gilts	Entire Males	Barrows	Gilts	Entire Males	Barrows	Gilts	Entire Males
NE content of the diet (kcal/kg)[a]	2,475	2,475	2,475	2,475	2,475	2,475	2,475	2,475	2,475
Effective DE content of diet (kcal/kg)[a]	3,402	3,402	3,402	3,402	3,402	3,402	3,402	3,402	3,402
Effective ME content of diet (kcal/kg)[a]	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300
Estimated effective ME intake (kcal/day)	7,282	6,658	6,466	8,603	7,913	7,657	9,495	8,910	8,633
Estimated feed intake + wastage (g/day)[b]	2,323	2,124	2,062	2,744	2,524	2,442	3,029	2,842	2,754
Body weight gain (g/day)	917	866	872	936	897	922	879	853	906
Body protein deposition (g/day)	145	145	150	139	144	156	119	126	148
				Calcium and phosphorus (g/day)					
Total calcium	12.27	12.22	12.59	12.91	13.36	14.26	12.47	13.11	15.01
STTD phosphorus[c]	5.71	5.68	5.85	6.00	6.21	6.63	5.80	6.10	6.98
ATTD phosphorus[d,e]	4.81	4.81	4.97	5.04	5.25	5.63	4.84	5.12	5.91
Total phosphorus[e]	10.95	10.65	10.77	11.85	11.86	12.30	11.88	12.05	13.13
				Amino acids[f,g]					
				Standardized ileal digestible basis (g/day)					
Arginine	8.2	8.0	7.9	8.3	8.4	8.7	7.6	7.9	8.8
Histidine	6.1	6.0	6.0	6.2	6.3	6.5	5.7	5.9	6.6
Isoleucine	9.4	9.2	9.1	9.6	9.7	10.0	9.0	9.2	10.1
Leucine	18.0	17.7	17.5	18.3	18.7	19.2	16.9	17.5	19.4
Lysine	**17.8**	**17.5**	**17.3**	**18.1**	**18.4**	**19.0**	**16.6**	**17.2**	**19.2**
Methionine	5.1	5.0	5.0	5.2	5.3	5.5	4.8	5.0	5.5
Methionine + cysteine	10.2	9.9	9.8	10.4	10.6	10.8	9.8	10.1	11.0
Phenylalanine	10.7	10.5	10.4	10.9	11.1	11.4	10.2	10.5	11.5
Phenylalanine + tyrosine	16.8	16.5	16.3	17.2	17.5	17.9	16.0	16.5	18.2
Threonine	11.1	10.8	10.6	11.6	11.6	11.8	11.1	11.2	12.1
Tryptophan	3.1	3.0	3.0	3.2	3.2	3.3	3.0	3.1	3.3
Valine	11.7	11.4	11.3	12.0	12.2	12.4	11.2	11.5	12.6
Total nitrogen	38.9	37.9	37.4	40.1	40.4	41.3	37.6	38.6	42.1
				Apparent ileal digestible basis (g/day)					
Arginine	7.2	7.1	7.1	7.2	7.4	7.7	6.4	6.7	7.6
Histidine	5.8	5.7	5.6	5.8	6.0	6.1	5.3	5.5	6.2
Isoleucine	8.8	8.6	8.5	8.9	9.1	9.4	8.2	8.5	9.4
Leucine	17.0	16.7	16.5	17.1	17.5	18.1	15.7	16.3	18.2
Lysine	**16.9**	**16.7**	**16.5**	**17.1**	**17.5**	**18.1**	**15.6**	**16.2**	**18.1**
Methionine	4.9	4.8	4.8	4.9	5.1	5.2	4.5	4.7	5.2
Methionine + cysteine	9.6	9.4	9.3	9.8	10.0	10.2	9.2	9.5	10.4
Phenylalanine	10.1	9.9	9.8	10.2	10.4	10.7	9.4	9.7	10.8
Phenylalanine + tyrosine	15.9	15.6	15.4	16.1	16.4	16.9	14.9	15.4	17.0
Threonine	9.9	9.7	9.5	10.2	10.3	10.5	9.6	9.8	10.7
Tryptophan	2.8	2.8	2.7	2.9	2.9	3.0	2.7	2.8	3.0
Valine	10.7	10.5	10.3	10.8	11.0	11.3	10.0	10.3	11.4
Total nitrogen	34.1	33.5	33.1	34.6	35.3	36.2	31.9	33.0	36.5

TABLE 16-2B Continued

Body Weight Range (kg)	50 to 75			75 to 100			100 to 135		
Gender	Barrows	Gilts	Entire Males	Barrows	Gilts	Entire Males	Barrows	Gilts	Entire Males
				Total basis (g/day)					
Arginine	9.3	9.0	8.9	9.5	9.6	9.8	8.9	9.1	10.0
Histidine	7.2	7.0	6.9	7.3	7.4	7.6	6.9	7.1	7.8
Isoleucine	11.0	10.7	10.5	11.3	11.4	11.6	10.6	10.9	11.9
Leucine	20.7	20.3	20.0	21.1	21.5	22.0	19.6	20.2	22.3
Lysine	**20.5**	**20.1**	**19.9**	**20.9**	**21.3**	**21.8**	**19.4**	**20.0**	**22.1**
Methionine	5.9	5.8	5.8	6.1	6.2	6.3	5.7	5.9	6.4
Methionine + cysteine	12.1	11.8	11.6	12.5	12.6	12.9	11.9	12.1	13.2
Phenylalanine	12.4	12.1	12.0	12.7	12.9	13.2	11.9	12.2	13.4
Phenylalanine + tyrosine	19.9	19.4	19.2	20.5	20.7	21.2	19.3	19.8	21.6
Threonine	13.5	13.1	12.8	14.2	14.1	14.3	13.6	13.8	14.8
Tryptophan	3.5	3.4	3.4	3.7	3.7	3.7	3.5	3.5	3.8
Valine	13.9	13.5	13.3	14.3	14.4	14.7	13.5	13.8	15.0
Total nitrogen	46.7	45.4	44.7	48.5	48.7	49.5	46.1	46.9	50.8

[a]Dietary energy contents relate to corn and soybean meal–based diets. Effective DE and effective ME contents are calculated from NE contents using fixed conversion values for pigs above 25 kg body weight. For corn and soybean meal–based diets, effective DE and effective ME contents are similar to actual DE and ME contents. The optimum dietary energy content varies with availability and costs of local feed ingredients. When using alternative feed ingredients, it is suggested that diets be formulated based on NE contents and nutrient requirements be adjusted to maintain constant nutrient-to-net energy ratios.

[b]Assumes 5% feed wastage.

[c]Standardized total tract digestible.

[d]Apparent total tract digestible.

[e]Apparent total tract digestible and total phosphorus requirements apply to corn and soybean meal–based diets only and have been calculated from standardized total tract digestible phosphorus requirements and nutrient profiles in corn, dehulled solvent-extracted soybean meal, and dicalcium phosphate. Diets were assumed to contain 0.1% added lysine·HCl and 3% added vitamins and minerals. Corn and soybean meal levels were calculated to meet standardized ileal digestible lysine requirements, and dicalcium phosphate amounts were varied to meet requirements for standardized total tract digestible phosphorus.

[f]The requirements are estimated from the growth model.

[g]Apparent ileal digestible and total amino acid requirements apply to corn and soybean meal–based diets only and have been calculated from standardized ileal digestible amino acid requirements and amino acid contents in corn and dehulled solvent-extracted soybean meal–based diets with 0.1% added lysine·HCl and containing 3% added vitamins and minerals. For each amino acid, dietary levels of corn and soybean meal levels and nutrient requirements were calculated to meet standardized ileal digestible requirements.

TABLE 16-3A Dietary Calcium, Phosphorus, and Amino Acid Requirements of Pigs with Different Mean Whole-Body Protein Depositions from 25 to 125 kg and of Different Weights When Allowed Feed Ad Libitum (90% dry matter)

Body Weight Range (kg)	50 to 75			75 to 100			100 to 135		
Mean Protein Deposition (g/day)	115	135	155	115	135	155	115	135	155
NE content of the diet (kcal/kg)[a]	2,475	2,475	2,475	2,475	2,475	2,475	2,475	2,475	2,475
Effective DE content of diet (kcal/kg)[a]	3,402	3,402	3,402	3,402	3,402	3,402	3,402	3,402	3,402
Effective ME content of diet (kcal/kg)[a]	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300
Estimated effective ME intake (kcal/day)	6,980	6,989	6,982	8,254	8,265	8,250	9,204	9,196	9,197
Estimated feed intake + wastage (g/day)[b]	2,226	2,229	2,227	2,633	2,636	2,632	2,936	2,933	2,934
Body weight gain (g/day)	817	900	982	842	917	994	804	867	930
Body protein deposition (g/day)	125	147	168	121	141	163	104	122	140
				Calcium and phosphorus (%)					
Total calcium	0.51	0.59	0.66	0.46	0.52	0.59	0.40	0.46	0.52
STTD phosphorus[c]	0.24	0.27	0.31	0.21	0.24	0.28	0.19	0.21	0.24
ATTD phosphorus[d,e]	0.20	0.23	0.26	0.18	0.21	0.23	0.15	0.18	0.20
Total phosphorus[e]	0.47	0.52	0.56	0.43	0.47	0.52	0.39	0.43	0.46
				Amino acids[f,g]					
				Standardized ileal digestible basis (%)					
Arginine	0.36	0.39	0.41	0.31	0.33	0.36	0.26	0.28	0.30
Histidine	0.27	0.29	0.31	0.23	0.25	0.27	0.19	0.21	0.22
Isoleucine	0.41	0.45	0.47	0.36	0.39	0.41	0.30	0.33	0.35
Leucine	0.79	0.85	0.91	0.68	0.74	0.79	0.57	0.62	0.66
Lysine	**0.78**	**0.85**	**0.91**	**0.67**	**0.73**	**0.78**	**0.56**	**0.61**	**0.65**
Methionine	0.22	0.24	0.26	0.19	0.21	0.23	0.16	0.18	0.19
Methionine + cysteine	0.45	0.48	0.51	0.39	0.42	0.45	0.33	0.36	0.38
Phenylalanine	0.47	0.51	0.54	0.41	0.44	0.47	0.34	0.37	0.39
Phenylalanine + tyrosine	0.74	0.80	0.85	0.64	0.69	0.74	0.54	0.58	0.62
Threonine	0.49	0.52	0.55	0.43	0.46	0.49	0.38	0.40	0.42
Tryptophan	0.14	0.15	0.16	0.12	0.13	0.14	0.10	0.11	0.12
Valine	0.51	0.55	0.59	0.45	0.48	0.51	0.38	0.41	0.43
Total nitrogen	1.71	1.84	1.95	1.50	1.61	1.71	1.28	1.37	1.44
				Apparent ileal digestible basis (%)					
Arginine	0.31	0.34	0.37	0.26	0.29	0.32	0.21	0.24	0.26
Histidine	0.25	0.27	0.29	0.22	0.24	0.25	0.18	0.19	0.21
Isoleucine	0.38	0.42	0.45	0.33	0.36	0.39	0.28	0.30	0.32
Leucine	0.74	0.81	0.87	0.64	0.69	0.75	0.53	0.57	0.62
Lysine	**0.74**	**0.81**	**0.87**	**0.63**	**0.69**	**0.74**	**0.52**	**0.57**	**0.61**
Methionine	0.21	0.23	0.25	0.18	0.20	0.22	0.15	0.16	0.18
Methionine + cysteine	0.42	0.46	0.49	0.37	0.40	0.42	0.31	0.33	0.35
Phenylalanine	0.44	0.48	0.51	0.38	0.41	0.44	0.32	0.34	0.37
Phenylalanine + tyrosine	0.69	0.75	0.80	0.60	0.65	0.70	0.50	0.54	0.58
Threonine	0.44	0.47	0.50	0.38	0.41	0.43	0.33	0.35	0.37
Tryptophan	0.12	0.13	0.14	0.11	0.12	0.12	0.09	0.10	0.10
Valine	0.47	0.51	0.54	0.40	0.44	0.47	0.34	0.36	0.39
Total nitrogen	1.50	1.62	1.73	1.29	1.40	1.49	1.08	1.16	1.24

TABLE 16-3A Continued

Body Weight Range (kg)	50 to 75			75 to 100			100 to 135		
Mean Protein Deposition (g/day)	115	135	155	115	135	155	115	135	155
				Total basis (%)					
Arginine	0.41	0.44	0.47	0.35	0.38	0.41	0.30	0.32	0.34
Histidine	0.31	0.34	0.36	0.27	0.30	0.32	0.23	0.25	0.27
Isoleucine	0.48	0.52	0.55	0.42	0.45	0.48	0.36	0.39	0.41
Leucine	0.90	0.98	1.05	0.78	0.85	0.91	0.66	0.71	0.76
Lysine	**0.89**	**0.97**	**1.04**	**0.78**	**0.84**	**0.90**	**0.65**	**0.71**	**0.76**
Methionine	0.26	0.28	0.30	0.23	0.25	0.26	0.19	0.21	0.22
Methionine + cysteine	0.53	0.57	0.61	0.47	0.50	0.53	0.40	0.43	0.45
Phenylalanine	0.54	0.59	0.63	0.48	0.51	0.55	0.40	0.43	0.46
Phenylalanine + tyrosine	0.87	0.94	1.00	0.77	0.82	0.88	0.65	0.70	0.74
Threonine	0.60	0.64	0.67	0.53	0.56	0.59	0.47	0.49	0.51
Tryptophan	0.16	0.17	0.18	0.14	0.15	0.16	0.12	0.13	0.13
Valine	0.61	0.65	0.69	0.53	0.57	0.61	0.46	0.49	0.52
Total nitrogen	2.05	2.20	2.33	1.82	1.94	2.05	1.57	1.67	1.75

[a]Dietary energy contents relate to corn and soybean meal–based diets. Effective DE and effective ME contents are calculated from NE contents using fixed conversion values for pigs above 25 kg body weight. For corn and soybean meal–based diets, effective DE and effective ME contents are similar to actual DE and ME contents. The optimum dietary energy content varies with availability and costs of local feed ingredients. When using alternative feed ingredients, it is suggested that diets be formulated based on NE contents and nutrient requirements be adjusted to maintain constant nutrient-to-net energy ratios.

[b]Assumes 5% feed wastage.

[c]Standardized total tract digestible.

[d]Apparent total tract digestible.

[e]Apparent total tract digestible and total phosphorus requirements apply to corn and soybean meal–based diets only and have been calculated from standardized total tract digestible phosphorus requirements and nutrient profiles in corn, dehulled solvent-extracted soybean meal, and dicalcium phosphate. Diets were assumed to contain 0.1% added lysine·HCl and 3% added vitamins and minerals. Corn and soybean meal levels were calculated to meet standardized ileal digestible lysine requirements, and dicalcium phosphate amounts were varied to meet requirements for standardized total tract digestible phosphorus.

[f]The requirements are estimated from the growth model.

[g]Apparent ileal digestible and total amino acid requirements apply to corn and soybean meal–based diets only and have been calculated from standardized ileal digestible amino acid requirements and amino acid contents in corn and dehulled solvent-extracted soybean meal–based diets with 0.1% added lysine·HCl and containing 3% added vitamins and minerals. For each amino acid, dietary levels of corn and soybean meal levels and nutrient requirements were calculated to meet standardized ileal digestible requirements.

TABLE 16-3B Daily Calcium, Phosphorus, and Amino Acid Requirements of Pigs with Different Mean Whole-Body Protein Depositions from 25 to 125 kg and of Different Weights When Allowed Feed Ad Libitum (90% dry matter)

Body Weight Range (kg)	50 to 75			75 to 100			100 to 135		
Mean Protein Deposition (g/day)	115	135	155	115	135	155	115	135	155
NE content of the diet (kcal/kg)[a]	2,475	2,475	2,475	2,475	2,475	2,475	2,475	2,475	2,475
Effective DE content of diet (kcal/kg)[a]	3,402	3,402	3,402	3,402	3,402	3,402	3,402	3,402	3,402
Effective ME content of diet (kcal/kg)[a]	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300
Estimated effective ME intake (kcal/day)	6,980	6,989	6,982	8,254	8,265	8,250	9,204	9,196	9,197
Estimated feed intake + wastage (g/day)[b]	2,226	2,229	2,227	2,633	2,636	2,632	2,936	2,933	2,934
Body weight gain (g/day)	817	900	982	842	917	994	804	867	930
Body protein deposition (g/day)	125	147	168	121	141	163	104	122	140
				Calcium and phosphorus (g/day)					
Total calcium	10.80	12.43	13.99	11.45	13.14	14.83	11.21	12.80	14.39
STTD phosphorus[c]	5.02	5.78	6.51	5.33	6.11	6.90	5.21	5.95	6.69
ATTD phosphorus[d,e]	4.21	4.89	5.54	4.44	5.15	5.85	4.32	4.98	5.64
Total phosphorus[e]	9.91	10.92	11.88	10.80	11.86	12.90	10.98	11.97	12.94
				Amino acids[f,g]					
				Standardized ileal digestible basis (g/day)					
Arginine	7.5	8.2	8.8	7.7	8.4	9.0	7.2	7.8	8.3
Histidine	5.6	6.2	6.6	5.8	6.3	6.7	5.4	5.8	6.2
Isoleucine	8.7	9.4	10.0	9.0	9.7	10.3	8.4	9.1	9.7
Leucine	16.6	18.1	19.3	17.0	18.5	19.8	15.9	17.2	18.4
Lysine	**16.4**	**17.9**	**19.2**	**16.8**	**18.3**	**19.6**	**15.6**	**16.9**	**18.1**
Methionine	4.7	5.2	5.5	4.8	5.3	5.7	4.5	4.9	5.2
Methionine + cysteine	9.4	10.2	10.8	9.8	10.5	11.2	9.2	9.9	10.5
Phenylalanine	9.9	10.8	11.5	10.2	11.0	11.8	9.6	10.3	11.0
Phenylalanine + tyrosine	15.6	16.9	18.0	16.0	17.3	18.5	15.1	16.3	17.3
Threonine	10.4	11.1	11.7	10.9	11.6	12.2	10.5	11.1	11.7
Tryptophan	2.9	3.1	3.3	3.0	3.2	3.4	2.8	3.0	3.2
Valine	10.9	11.7	12.5	11.2	12.1	12.9	10.6	11.4	12.1
Total nitrogen	36.2	39.0	41.3	37.5	40.3	42.7	35.7	38.1	40.3
				Apparent ileal digestible basis (g/day)					
Arginine	6.6	7.3	7.8	6.6	7.3	7.9	6.0	6.6	7.1
Histidine	5.3	5.8	6.2	5.4	5.9	6.3	5.0	5.4	5.8
Isoleucine	8.1	8.9	9.5	8.3	9.0	9.7	7.7	8.4	8.9
Leucine	15.6	17.1	18.3	15.9	17.3	18.6	14.7	16.0	17.1
Lysine	**15.6**	**17.1**	**18.3**	**15.8**	**17.3**	**18.6**	**14.6**	**15.9**	**17.1**
Methionine	4.5	4.9	5.3	4.6	5.0	5.4	4.2	4.6	4.9
Methionine + cysteine	8.9	9.7	10.3	9.2	9.9	10.6	8.7	9.3	9.9
Phenylalanine	9.3	10.1	10.8	9.5	10.3	11.1	8.8	9.6	10.2
Phenylalanine + tyrosine	14.7	15.9	17.0	15.0	16.3	17.4	14.0	15.1	16.1
Threonine	9.2	9.9	10.5	9.6	10.3	10.9	9.1	9.7	10.3
Tryptophan	2.6	2.8	3.0	2.7	2.9	3.1	2.5	2.7	2.9
Valine	9.9	10.7	11.4	10.1	10.9	11.7	9.4	10.2	10.8
Total nitrogen	31.6	34.3	36.6	32.3	35.0	37.3	30.1	32.5	34.5

TABLE 16-3B Continued

Body Weight Range (kg)	50 to 75			75 to 100			100 to 135		
Mean Protein Deposition (g/day)	115	135	155	115	135	155	115	135	155
				Total basis (g/day)					
Arginine	8.6	9.3	9.9	8.9	9.6	10.2	8.4	9.0	9.6
Histidine	6.6	7.2	7.7	6.8	7.4	7.9	6.5	7.0	7.4
Isoleucine	10.2	11.0	11.6	10.6	11.4	12.1	10.1	10.8	11.4
Leucine	19.1	20.8	22.2	19.6	21.3	22.8	18.4	19.9	21.2
Lysine	**18.9**	**20.6**	**22.0**	**19.4**	**21.1**	**22.6**	**18.2**	**19.7**	**21.1**
Methionine	5.5	6.0	6.4	5.7	6.1	6.6	5.3	5.8	6.2
Methionine + cysteine	11.2	12.1	12.8	11.7	12.6	13.3	11.2	12.0	12.7
Phenylalanine	11.5	12.5	13.3	11.9	12.8	13.7	11.2	12.1	12.8
Phenylalanine + tyrosine	18.5	20.0	21.2	19.2	20.6	21.9	18.2	19.5	20.7
Threonine	12.6	13.4	14.1	13.3	14.1	14.9	13.0	13.7	14.3
Tryptophan	3.3	3.5	3.7	3.4	3.7	3.9	3.3	3.5	3.7
Valine	12.9	13.9	14.7	13.4	14.4	15.2	12.7	13.6	14.4
Total nitrogen	43.5	46.6	49.2	45.5	48.6	51.3	43.8	46.5	48.9

[a]Dietary energy contents relate to corn and soybean meal–based diets. Effective DE and effective ME contents are calculated from NE contents using fixed conversion values for pigs below and above 25 kg body weight. For corn and soybean meal–based diets, effective DE and effective ME contents are similar to actual DE and ME contents. The optimum dietary energy content varies with availability and costs of local feed ingredients. When using alternative feed ingredients it is suggested that diets be formulated based on NE contents and nutrient requirements be adjusted to maintain constant nutrient-to-net energy ratios.

[b]Assumes 5% feed wastage.

[c]Standardized total tract digestible.

[d]Apparent total tract digestible.

[e]Apparent total tract digestible and total phosphorus requirements apply to corn and soybean meal–based diets only and have been calculated from standardized total tract digestible phosphorus requirements and nutrient profiles in corn, dehulled solvent-extracted soybean meal, and dicalcium phosphate. Diets were assumed to contain 0.1% added lysine·HCl and 3% added vitamins and minerals. Corn and soybean meal levels were calculated to meet standardized ileal digestible lysine requirements, and dicalcium phosphate amounts were varied to meet requirements for standardized total tract digestible phosphorus.

[f]The requirements are estimated from the growth model.

[g]Apparent ileal digestible and total amino acid requirements apply to corn and soybean meal–based diets only and have been calculated from standardized ileal digestible amino acid requirements and amino acid contents in corn and dehulled solvent-extracted soybean meal–based diets with 0.1% added lysine·HCl and containing 3% added vitamins and minerals. For each amino acid, dietary levels of corn and soybean meal levels and nutrient requirements were calculated to meet standardized ileal digestible requirements.

TABLE 16-4A Dietary Calcium, Phosphorus, and Amino Acid Requirements of Entire Males Immunized Against Gonadotrophin Releasing Hormone or Fed Ractopamine, and Barrows and Gilts Fed Ractopamine, When Allowed Feed Ad Libitum (90% dry matter)

	Entire Males Immunized	Entire Males Fed 5 ppm Ractopamine	Entire Males Fed 10 ppm Ractopamine	Barrows and Gilts Fed 5 ppm Ractopamine	Barrows and Gilts Fed 10 ppm Ractopamine
Body Weight Range (kg)	105-135	115-135	115-135	115-135	115-135
NE content of the diet (kcal/kg)[a]	2,475	2,475	2,475	2,475	2,475
Effective DE content of diet (kcal/kg)[a]	3,402	3,402	3,402	3,402	3,402
Effective ME content of diet (kcal/kg)[a]	3,300	3,300	3,300	3,300	3,300
Estimated effective ME intake (kcal/day)	10,203	8,722	8,647	9,262	9,181
Estimated feed intake + wastage (g/day)[b]	3,255	2,782	2,758	2,954	2,929
Body weight gain (g/day)	1,023	1,029	1,064	957	983
Body protein deposition (g/day)	137	187	199	152	161
			Calcium and phosphorus (%)		
Total calcium	0.47	0.71	0.75	0.56	0.59
STTD phosphorus[c]	0.22	0.33	0.35	0.26	0.27
ATTD phosphorus[d,e]	0.18	0.28	0.30	0.22	0.23
Total phosphorus[e]	0.43	0.59	0.62	0.49	0.52
			Amino acids[f,g]		
			Standardized ileal digestible basis (%)		
Arginine	0.27	0.42	0.45	0.34	0.37
Histidine	0.20	0.31	0.33	0.25	0.27
Isoleucine	0.32	0.51	0.54	0.42	0.45
Leucine	0.60	0.93	1.00	0.77	0.82
Lysine	**0.59**	**0.94**	**1.01**	**0.77**	**0.83**
Methionine	0.17	0.28	0.30	0.23	0.24
Methionine + cysteine	0.35	0.54	0.58	0.45	0.48
Phenylalanine	0.36	0.56	0.60	0.46	0.49
Phenylalanine + tyrosine	0.57	0.88	0.95	0.73	0.78
Threonine	0.39	0.57	0.61	0.49	0.52
Tryptophan	0.11	0.17	0.18	0.14	0.15
Valine	0.40	0.61	0.65	0.50	0.54
Total nitrogen	1.33	1.96	2.08	1.64	1.74
			Apparent ileal digestible basis (%)		
Arginine	0.23	0.37	0.40	0.30	0.32
Histidine	0.19	0.29	0.31	0.24	0.25
Isoleucine	0.29	0.48	0.52	0.39	0.42
Leucine	0.56	0.89	0.95	0.72	0.77
Lysine	**0.56**	**0.90**	**0.97**	**0.73**	**0.79**
Methionine	0.16	0.27	0.29	0.21	0.23
Methionine + cysteine	0.32	0.51	0.55	0.42	0.45
Phenylalanine	0.33	0.53	0.57	0.43	0.46
Phenylalanine + tyrosine	0.53	0.84	0.90	0.68	0.73
Threonine	0.34	0.52	0.55	0.43	0.46
Tryptophan	0.09	0.15	0.16	0.13	0.14
Valine	0.35	0.56	0.60	0.46	0.49
Total nitrogen	1.13	1.74	1.86	1.42	1.52

TABLE 16-4A Continued

	Entire Males Immunized	Entire Males Fed 5 ppm Ractopamine	Entire Males Fed 10 ppm Ractopamine	Barrows and Gilts Fed 5 ppm Ractopamine	Barrows and Gilts Fed 10 ppm Ractopamine
Body Weight Range (kg)	105-135	115-135	115-135	115-135	115-135
			Total basis (%)		
Arginine	0.32	0.47	0.50	0.39	0.41
Histidine	0.24	0.36	0.38	0.30	0.32
Isoleucine	0.38	0.59	0.63	0.49	0.52
Leucine	0.70	1.07	1.15	0.88	0.94
Lysine	**0.69**	**1.08**	**1.16**	**0.89**	**0.95**
Methionine	0.20	0.32	0.34	0.26	0.28
Methionine + cysteine	0.42	0.63	0.68	0.53	0.57
Phenylalanine	0.42	0.64	0.69	0.53	0.57
Phenylalanine + tyrosine	0.68	1.04	1.11	0.86	0.92
Threonine	0.48	0.69	0.74	0.59	0.63
Tryptophan	0.12	0.19	0.20	0.16	0.17
Valine	0.48	0.72	0.76	0.60	0.64
Total nitrogen	1.62	2.34	2.48	1.97	2.08

[a]Dietary energy contents relate to corn and soybean meal–based diets. Effective DE and effective ME contents are calculated from NE contents using fixed conversion values for pigs above 25 kg body weight. For corn and soybean meal-based diets, effective DE and effective ME contents are similar to actual DE and ME contents. The optimum dietary energy content varies with availability and costs of local feed ingredients. When using alternative feed ingredients, it is suggested that diets be formulated based on NE contents and nutrient requirements be adjusted to maintain constant nutrient-to-net energy ratios.

[b]Assumes 5% feed wastage.

[c]Standardized total tract digestible.

[d]Apparent total tract digestible.

[e]Apparent total tract digestible and total phosphorus requirements apply to corn and soybean meal–based diets only and have been calculated from standardized total tract digestible phosphorus requirements and nutrient profiles in corn, dehulled solvent-extracted soybean meal, and dicalcium phosphate. Diets were assumed to contain 0.1% added lysine·HCl and 3% added vitamins and minerals. Corn and soybean meal levels were calculated to meet standardized ileal digestible lysine requirements, and dicalcium phosphate amounts were varied to meet requirements for standardized total tract digestible phosphorus.

[f]The requirements are estimated from the growth model.

[g]Apparent ileal digestible and total amino acid requirements apply to corn and soybean meal–based diets only and have been calculated from standardized ileal digestible amino acid requirements and amino acid contents in corn and dehulled solvent-extracted soybean meal–based diets with 0.1% added lysine·HCl and containing 3% added vitamins and minerals. For each amino acid, dietary levels of corn and soybean meal levels and nutrient requirements were calculated to meet standardized ileal digestible requirements.

TABLE 16-4B Daily Calcium, Phosphorus, and Amino Acid Requirements of Entire Males Immunized Against Gonadotrophin Releasing Hormone or Fed Ractopamine, and Barrows and Gilts Fed Ractopamine, When Allowed Feed Ad Libitum (90% dry matter)

	Entire Males Immunized	Entire Males Fed 5 ppm Ractopamine	Entire Males Fed 10 ppm Ractopamine	Barrows and Gilts Fed 5 ppm Ractopamine	Barrows and Gilts Fed 10 ppm Ractopamine
Body Weight Range (kg)	105-135	115-135	115-135	115-135	115-135
NE content of the diet (kcal/kg)[a]	2,475	2,475	2,475	2,475	2,475
Effective DE content of diet (kcal/kg)[a]	3,402	3,402	3,402	3,402	3,402
Effective ME content of diet (kcal/kg)[a]	3,300	3,300	3,300	3,300	3,300
Estimated effective ME intake (kcal/day)	10,203	8,722	8,647	9,262	9,181
Estimated feed intake + wastage (g/day)[b]	3,255	2,782	2,758	2,954	2,929
Body weight gain (g/day)	1,023	1,029	1,064	957	983
Body protein deposition (g/day)	137	187	199	152	161
			Calcium and phosphorus (g/day)		
Total calcium	14.44	18.73	19.76	15.60	16.43
STTD phosphorus[c]	6.72	8.71	9.19	7.26	7.64
ATTD phosphorus[d,e]	5.63	7.44	7.86	6.13	6.47
Total phosphorus[e]	13.38	15.61	16.27	13.85	14.38
			Amino acids[f,g]		
			Standardized ileal digestible basis (g/day)		
Arginine	8.4	11.0	11.7	9.6	10.2
Histidine	6.3	8.2	8.6	7.1	7.5
Isoleucine	9.8	13.4	14.3	11.7	12.5
Leucine	18.6	24.7	26.3	21.5	22.8
Lysine	**18.3**	**24.9**	**26.5**	**21.6**	**23.0**
Methionine	5.3	7.3	7.8	6.3	6.8
Methionine + cysteine	10.7	14.2	15.1	12.5	13.3
Phenylalanine	11.2	14.7	15.6	12.9	13.6
Phenylalanine + tyrosine	17.6	23.3	24.8	20.4	21.7
Threonine	12.0	15.2	16.0	13.6	14.4
Tryptophan	3.3	4.4	4.7	3.9	4.1
Valine	12.3	16.1	17.1	14.1	15.0
Total nitrogen	41.1	51.8	54.6	45.9	48.3
			Apparent ileal digestible basis (g/day)		
Arginine	7.1	9.9	10.5	8.4	9.0
Histidine	5.9	7.7	8.2	6.7	7.0
Isoleucine	9.0	12.6	13.5	11.0	11.7
Leucine	17.3	23.4	25.0	20.2	21.5
Lysine	**17.2**	**23.8**	**25.4**	**20.5**	**21.9**
Methionine	5.0	7.0	7.5	6.0	6.5
Methionine + cysteine	10.0	13.5	14.4	11.8	12.6
Phenylalanine	10.3	13.9	14.8	12.1	12.8
Phenylalanine + tyrosine	16.3	22.1	23.5	19.2	20.4
Threonine	10.5	13.7	14.5	12.1	12.9
Tryptophan	2.9	4.0	4.3	3.5	3.8
Valine	10.9	14.8	15.7	12.8	13.6
Total nitrogen	34.9	45.9	48.7	40.0	42.3

TABLE 16-4B Continued

Body Weight Range (kg)	Entire Males Immunized 105-135	Entire Males Fed 5 ppm Ractopamine 115-135	Entire Males Fed 10 ppm Ractopamine 115-135	Barrows and Gilts Fed 5 ppm Ractopamine 115-135	Barrows and Gilts Fed 10 ppm Ractopamine 115-135
			Total basis (g/day)		
Arginine	9.8	12.4	13.1	11.0	11.5
Histidine	7.6	9.5	10.0	8.4	8.8
Isoleucine	11.6	15.5	16.5	13.7	14.5
Leucine	21.5	28.3	30.1	24.7	26.2
Lysine	**21.4**	**28.5**	**30.3**	**24.8**	**26.4**
Methionine	6.3	8.4	8.9	7.3	7.8
Methionine + cysteine	12.9	16.8	17.8	14.9	15.8
Phenylalanine	13.1	17.0	18.0	14.9	15.8
Phenylalanine + tyrosine	21.1	27.4	29.1	24.2	25.6
Threonine	14.8	18.3	19.3	16.6	17.4
Tryptophan	3.8	4.9	5.3	4.4	4.7
Valine	14.7	18.9	20.0	16.8	17.7
Total nitrogen	50.2	61.8	65.0	55.3	58.0

[a]Dietary energy contents relate to corn and soybean meal–based diets. Effective DE and effective ME contents are calculated from NE contents using fixed conversion values for pigs above 25 kg body weight. For corn and soybean meal-based diets, effective DE and effective ME contents are similar to actual DE and ME contents. The optimum dietary energy content varies with availability and costs of local feed ingredients. When using alternative feed ingredients, it is suggested that diets be formulated based on NE contents and nutrient requirements be adjusted to maintain constant nutrient-to-net energy ratios.

[b]Assumes 5% feed wastage.

[c]Standardized total tract digestible.

[d]Apparent total tract digestible.

[e]Apparent total tract digestible and total phosphorus requirements apply to corn and soybean meal–based diets only and have been calculated from standardized total tract digestible phosphorus requirements and nutrient profiles in corn, dehulled solvent-extracted soybean meal, and dicalcium phosphate. Diets were assumed to contain 0.1% added lysine·HCl and 3% added vitamins and minerals. Corn and soybean meal levels were calculated to meet standardized ileal digestible lysine requirements, and dicalcium phosphate amounts were varied to meet requirements for standardized total tract digestible phosphorus.

[f]The requirements are estimated from the growth model.

[g]Apparent ileal digestible and total amino acid requirements apply to corn and soybean meal–based diets only and have been calculated from standardized ileal digestible amino acid requirements and amino acid contents in corn and dehulled solvent-extracted soybean meal–based diets with 0.1% added lysine·HCl and containing 3% added vitamins and minerals. For each amino acid, dietary levels of corn and soybean meal levels and nutrient requirements were calculated to meet standardized ileal digestible requirements.

TABLE 16-5A Dietary Mineral, Vitamin, and Fatty Acid Requirements of Growing Pigs Allowed Feed Ad Libitum (90% dry matter)

	Body Weight Range (kg)						
Item	5-7	7-11	11-25	25-50	50-75	75-100	100-135
NE content of the diet (kcal/kg)[a]	2,448	2,448	2,412	2,475	2,475	2,475	2,475
Effective DE content of diet (kcal/kg)[a]	3,542	3,542	3,490	3,402	3,402	3,402	3,402
Effective ME content of diet (kcal/kg)[a]	3,400	3,400	3,350	3,300	3,300	3,300	3,300
Estimated effective ME intake (kcal/day)	904	1,592	3,033	4,959	6,989	8,265	9,196
Estimated feed intake + wastage (g/day)[b]	280	493	953	1,582	2,229	2,636	2,933
Body weight gain (g/day)	210	335	585	758	900	917	867
Body protein deposition (g/day)	—	—	—	128	147	141	122
	Requirements (% or amount per kilogram of diet)						
Mineral elements							
Sodium (%)	0.40	0.35	0.28	0.10	0.10	0.10	0.10
Chloride (%)	0.50	0.45	0.32	0.08	0.08	0.08	0.08
Magnesium (%)	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Potassium (%)	0.30	0.28	0.26	0.23	0.19	0.17	0.17
Copper (mg/kg)	6.00	6.00	5.00	4.00	3.50	3.00	3.00
Iodine (mg/kg)	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Iron (mg/kg)	100	100	100	60	50	40	40
Manganese (mg/kg)	4.00	4.00	3.00	2.00	2.00	2.00	2.00
Selenium (mg/kg)	0.30	0.30	0.25	0.20	0.15	0.15	0.15
Zinc (mg/kg)	100	100	80	60	50	50	50
Vitamins							
Vitamin A (IU/kg)[c]	2,200	2,200	1,750	1,300	1,300	1,300	1,300
Vitamin D (IU/kg)[d]	220	220	200	150	150	150	150
Vitamin E (IU/kg)[e]	16	16	11	11	11	11	11
Vitamin K (menadione) (mg/kg)	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Biotin (mg/kg)	0.08	0.05	0.05	0.05	0.05	0.05	0.05
Choline (g/kg)	0.60	0.50	0.40	0.30	0.30	0.30	0.30
Folacin (mg/kg)	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Niacin, available (mg/kg)[f]	30.00	30.00	30.00	30.00	30.00	30.00	30.00
Pantothenic acid (mg/kg)	12.00	10.00	9.00	8.00	7.00	7.00	7.00
Riboflavin (mg/kg)	4.00	3.50	3.00	2.50	2.00	2.00	2.00
Thiamin (mg/kg)	1.50	1.00	1.00	1.00	1.00	1.00	1.00
Vitamin B_6 (mg/kg)	7.00	7.00	3.00	1.00	1.00	1.00	1.00
Vitamin B_{12} (μg/kg)	20.00	17.50	15.00	10.00	5.00	5.00	5.00
Linoleic acid (%)	0.10	0.10	0.10	0.10	0.10	0.10	0.10

[a]Dietary energy contents relate to corn and soybean meal–based diets. Effective DE and effective ME contents are calculated from NE contents using fixed conversion values for pigs below and above 25 kg body weight. For corn and soybean meal–based diets, effective DE and effective ME contents are similar to actual DE and ME contents. The optimum dietary energy content varies with availability and costs of local feed ingredients. When using alternative feed ingredients, it is suggested that diets be formulated based on NE contents and nutrient requirements be adjusted to maintain constant nutrient-to-net energy ratios.

[b]Assumes 5% feed wastage.

[c]1 IU vitamin A = 0.30 μg retinol or 0.344 μg retinyl acetate. Vitamin A activity (also known as retinol equivalents) is also provided by β-carotene (see Vitamins chapter).

[d]1 IU vitamin D_2 or D_3 = 0.025 μg.

[e]1 IU vitamin E = 0.67 mg of D-α-tocopherol or 1 mg of DL-α-tocopheryl acetate. Recent research with swine has shown a substantial difference in the activity of natural and synthetic α-tocopheryl acetates (see Vitamins chapter).

[f]The niacin in corn, grain sorghum, wheat, and barley is unavailable. Similarly, the niacin in byproducts made from these cereal grains is poorly available unless the byproducts have undergone fermentation of wet-milling process.

TABLE 16-5B Daily Mineral, Vitamin, and Fatty Acid Requirements of Growing Pigs Allowed Feed Ad Libitum (90% dry matter)

	Body Weight Range (kg)						
Item	5-7	7-11	11-25	25-50	50-75	75-100	100-135
NE content of the diet (kcal/kg)[a]	2,448	2,448	2,412	2,475	2,475	2,475	2,475
Effective DE content of diet (kcal/kg)[a]	3,542	3,542	3,490	3,402	3,402	3,402	3,402
Effective ME content of diet (kcal/kg)[a]	3,400	3,400	3,350	3,300	3,300	3,300	3,300
Estimated effective ME intake (kcal/day)	904	1,592	3,033	4,959	6,989	8,265	9,196
Estimated feed intake + wastage (g/day)[b]	280	493	953	1,582	2,229	2,636	2,933
Body weight gain (g/day)	210	335	585	758	900	917	867
Body protein deposition (g/day)	—	—	—	128	147	141	122
	Requirements (amount per day)						
Mineral elements							
Sodium (g)	1.06	1.64	2.53	1.50	2.12	2.51	2.79
Chloride (g)	1.33	2.11	2.90	1.20	1.69	2.00	2.23
Magnesium (g)	0.11	0.19	0.36	0.60	0.85	1.00	1.11
Potassium (g)	0.80	1.31	2.35	3.46	4.02	4.26	4.74
Copper (mg)	1.60	2.81	4.53	6.01	7.41	7.52	8.36
Iodine (mg)	0.04	0.07	0.13	0.21	0.30	0.35	0.39
Iron (mg)	26.6	46.8	90.5	90.2	105.9	100.2	111.5
Manganese (mg)	1.06	1.87	2.72	3.01	4.24	5.01	5.57
Selenium (mg)	0.08	0.14	0.23	0.30	0.32	0.38	0.42
Zinc (mg)	26.6	46.8	72.4	90.2	105.9	125.3	139.4
Vitamins							
Vitamin A (IU)[c]	585	1,030	1,584	1,954	2,753	3,257	3,623
Vitamin D (IU)[d]	59	103	181	225	318	376	418
Vitamin E (IU)[e]	4.3	7.5	10.0	16.5	23.3	27.6	30.7
Vitamin K (menadione) (mg)	0.13	0.23	0.45	0.75	1.06	1.25	1.39
Biotin (mg)	0.02	0.02	0.05	0.08	0.11	0.13	0.14
Choline (g)	0.16	0.23	0.36	0.45	0.64	0.75	0.84
Folacin (mg)	0.08	0.14	0.27	0.45	0.64	0.75	0.84
Niacin, available (mg)[f]	7.98	14.05	27.16	45.09	63.53	75.15	83.62
Pantothenic acid (mg)	3.19	4.68	8.15	12.02	14.82	17.54	19.51
Riboflavin (mg)	1.06	1.64	2.72	3.76	4.24	5.01	5.57
Thiamin (mg)	0.40	0.47	0.91	1.50	2.12	2.51	2.79
Vitamin B_6 (mg)	1.86	3.28	2.72	1.50	2.12	2.51	2.79
Vitamin B_{12} (μg)	5.32	8.20	13.58	15.03	10.59	12.53	13.94
Linoleic acid (g)	0.3	0.5	0.9	1.5	2.1	2.5	2.8

[a]Dietary energy contents relate to corn and soybean meal–based diets. Effective DE and effective ME contents are calculated from NE contents using fixed conversion values for pigs below and above 25 kg body weight. For corn and soybean meal–based diets, effective DE and effective ME contents are similar to actual DE and ME contents. The optimum dietary energy content varies with availability and costs of local feed ingredients. When using alternative feed ingredients, it is suggested that diets be formulated based on NE contents and nutrient requirements be adjusted to maintain constant nutrient-to-net energy ratios.

[b]Assumes 5% feed wastage.

[c]1 IU vitamin A = 0.30 μg retinol or 0.344 μg retinyl acetate. Vitamin A activity (also known as retinol equivalents) is also provided by β-carotene (see Vitamins chapter).

[d]1 IU vitamin D_2 or D_3 = 0.025 μg.

[e]1 IU vitamin E = 0.67 mg of D-α-tocopherol or 1 mg of DL-α-tocopheryl acetate. Recent research with swine has shown a substantial difference in the activity of natural and synthetic α-tocopheryl acetates (see Vitamins chapter).

[f]The niacin in corn, grain sorghum, wheat, and barley is unavailable. Similarly, the niacin in byproducts made from these cereal grains is poorly available unless the byproducts have undergone fermentation of wet-milling process.

TABLE 16-6A Dietary Calcium, Phosphorus, and Amino Acid Requirements of Gestating Sows (90% dry matter)[a]

Parity (body weight at breeding, kg)	1 (140)		2 (165)		3 (185)		4 + (205)					
Anticipated gestation weight gain (kg)	65		60		52.2		45		40		45	
Anticipated litter size[b]	12.5		13.5		13.5		13.5		13.5		15.5	
Days of gestation	< 90	> 90	< 90	> 90	< 90	> 90	< 90	> 90	< 90	> 90	< 90	> 90
NE content of the diet (kcal/kg)[a]	2,518	2,518	2,518	2,518	2,518	2,518	2,518	2,518	2,518	2,518	2,518	2,518
Effective DE content of diet (kcal/kg)[a]	3,388	3,388	3,388	3,388	3,388	3,388	3,388	3,388	3,388	3,388	3,388	3,388
Effective ME content of diet (kcal/kg)[a]	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300
Estimated effective ME intake (kcal/day)	6,678	7,932	6,928	8,182	6,928	8,182	6,897	8,151	6,427	7,681	6,521	7,775
Estimated feed intake + wastage (g/day)[c]	2,130	2,530	2,210	2,610	2,210	2,610	2,200	2,600	2,050	2,450	2,080	2,480
Body weight gain (g/day)	578	543	539	481	472	408	410	340	364	298	416	313
Calcium and phosphorus (%)												
Total calcium	0.61	0.83	0.54	0.78	0.49	0.72	0.43	0.67	0.46	0.71	0.46	0.75
STTD phosphorus[d]	0.27	0.36	0.24	0.34	0.21	0.31	0.19	0.29	0.20	0.31	0.20	0.33
ATTD phosphorus[e,f]	0.23	0.31	0.20	0.29	0.18	0.27	0.16	0.25	0.17	0.26	0.17	0.28
Total phosphorus[f]	0.49	0.62	0.45	0.58	0.41	0.55	0.38	0.52	0.40	0.54	0.40	0.56
Amino acids[g,h]												
Standardized ileal digestible basis (%)												
Arginine	0.28	0.37	0.23	0.32	0.19	0.28	0.17	0.24	0.17	0.25	0.17	0.26
Histidine	0.18	0.22	0.15	0.19	0.13	0.16	0.11	0.14	0.11	0.14	0.11	0.15
Isoleucine	0.30	0.36	0.25	0.32	0.22	0.27	0.19	0.24	0.19	0.24	0.20	0.26
Leucine	0.47	0.65	0.40	0.57	0.35	0.51	0.30	0.45	0.31	0.47	0.32	0.49
Lysine	**0.52**	**0.69**	**0.44**	**0.61**	**0.37**	**0.53**	**0.32**	**0.46**	**0.32**	**0.48**	**0.33**	**0.50**
Methionine	0.15	0.20	0.12	0.17	0.10	0.15	0.09	0.13	0.09	0.13	0.09	0.14
Methionine + cysteine	0.34	0.45	0.29	0.40	0.26	0.36	0.23	0.33	0.23	0.33	0.24	0.35
Phenylalanine	0.29	0.38	0.25	0.34	0.21	0.30	0.19	0.27	0.19	0.27	0.19	0.29
Phenylalanine + tyrosine	0.50	0.66	0.43	0.58	0.37	0.51	0.32	0.46	0.33	0.47	0.33	0.49
Threonine	0.37	0.48	0.33	0.43	0.29	0.39	0.27	0.36	0.27	0.36	0.28	0.38
Tryptophan	0.09	0.13	0.08	0.12	0.07	0.11	0.07	0.10	0.07	0.10	0.07	0.11
Valine	0.37	0.49	0.32	0.43	0.28	0.39	0.25	0.35	0.25	0.36	0.26	0.37
Total nitrogen	1.32	1.79	1.15	1.61	1.01	1.45	0.90	1.32	0.91	1.35	0.94	1.43
Apparent ileal digestible basis (%)												
Arginine	0.23	0.32	0.19	0.28	0.15	0.23	0.12	0.20	0.12	0.21	0.13	0.22
Histidine	0.17	0.21	0.14	0.18	0.11	0.15	0.10	0.13	0.10	0.13	0.10	0.14
Isoleucine	0.27	0.34	0.23	0.29	0.19	0.25	0.17	0.22	0.17	0.22	0.17	0.23
Leucine	0.43	0.60	0.36	0.53	0.30	0.46	0.26	0.41	0.27	0.42	0.28	0.45
Lysine	**0.49**	**0.66**	**0.40**	**0.57**	**0.34**	**0.49**	**0.29**	**0.43**	**0.29**	**0.44**	**0.30**	**0.47**
Methionine	0.14	0.19	0.11	0.16	0.09	0.14	0.08	0.12	0.08	0.12	0.08	0.13
Methionine + cysteine	0.32	0.43	0.27	0.38	0.24	0.34	0.21	0.31	0.21	0.31	0.22	0.33
Phenylalanine	0.26	0.35	0.22	0.31	0.19	0.27	0.16	0.24	0.16	0.25	0.17	0.26
Phenylalanine + tyrosine	0.46	0.62	0.39	0.54	0.33	0.47	0.29	0.42	0.29	0.43	0.30	0.45
Threonine	0.32	0.43	0.28	0.38	0.25	0.34	0.22	0.31	0.22	0.32	0.23	0.33
Tryptophan	0.08	0.12	0.07	0.11	0.06	0.10	0.05	0.09	0.06	0.09	0.06	0.10
Valine	0.33	0.44	0.28	0.39	0.24	0.34	0.21	0.31	0.21	0.31	0.22	0.33
Total nitrogen	1.12	1.58	0.95	1.41	0.82	1.25	0.72	1.12	0.73	1.15	0.75	1.23

TABLE 16-6A Continued

Parity (body weight at breeding, kg)	1 (140)		2 (165)		3 (185)		4 + (205)					
Anticipated gestation weight gain (kg)	65		60		52.2		45		40		45	
Anticipated litter size[b]	12.5		13.5		13.5		13.5		13.5		15.5	
Days of gestation	< 90	> 90	< 90	> 90	< 90	> 90	< 90	> 90	< 90	> 90	< 90	> 90
	Total basis (%)											
Arginine	0.32	0.42	0.27	0.37	0.23	0.32	0.20	0.29	0.21	0.29	0.21	0.31
Histidine	0.22	0.27	0.19	0.23	0.16	0.20	0.14	0.18	0.14	0.18	0.14	0.19
Isoleucine	0.36	0.43	0.31	0.38	0.27	0.33	0.24	0.29	0.24	0.30	0.24	0.31
Leucine	0.55	0.75	0.47	0.66	0.41	0.59	0.36	0.53	0.36	0.54	0.37	0.57
Lysine	**0.61**	**0.80**	**0.52**	**0.71**	**0.45**	**0.62**	**0.39**	**0.55**	**0.39**	**0.56**	**0.40**	**0.59**
Methionine	0.18	0.23	0.15	0.20	0.13	0.18	0.11	0.16	0.11	0.16	0.12	0.17
Methionine + cysteine	0.41	0.54	0.36	0.48	0.32	0.44	0.29	0.40	0.29	0.41	0.30	0.43
Phenylalanine	0.34	0.44	0.29	0.40	0.25	0.35	0.23	0.31	0.23	0.32	0.23	0.34
Phenylalanine + tyrosine	0.61	0.79	0.53	0.70	0.46	0.62	0.41	0.56	0.41	0.57	0.42	0.60
Threonine	0.46	0.58	0.41	0.53	0.37	0.48	0.34	0.44	0.34	0.45	0.35	0.47
Tryptophan	0.11	0.15	0.10	0.14	0.09	0.13	0.08	0.12	0.08	0.12	0.08	0.13
Valine	0.45	0.58	0.39	0.52	0.34	0.46	0.31	0.42	0.31	0.43	0.32	0.45
Total nitrogen	1.62	2.15	1.42	1.95	1.26	1.77	1.14	1.62	1.15	1.65	1.18	1.74

[a]Dietary energy contents relate to corn and soybean meal–based diets. Effective DE and effective ME contents are calculated from NE contents using fixed conversion values for sows. For corn and soybean meal–based diets, effective DE and effective ME contents are similar to actual DE and ME contents. The optimum dietary energy content varies with availability and costs of local feed ingredients. When using alternative feed ingredients, it is suggested that diets be formulated based on NE contents and nutrient requirements be adjusted to maintain constant nutrient-to-net energy ratios.

[b]Anticipated mean birth weight 1.40 kg.

[c]Assumes 5% feed wastage.

[d]Standardized total tract digestible.

[e]Apparent total tract digestible.

[f]Apparent total tract digestible and total phosphorus requirements apply to corn and soybean meal–based diets only and have been calculated from standardized total tract digestible phosphorus requirements and nutrient profiles in corn, dehulled solvent-extracted soybean meal, and dicalcium phosphate. Diets were assumed to contain 0.1% added lysine·HCl and 3% added vitamins and minerals. Corn and soybean meal levels were calculated to meet standardized ileal digestible lysine requirements, and dicalcium phosphate amounts were varied to meet requirements for standardized total tract digestible phosphorus.

[g]The requirements are estimated from the growth model.

[h]Apparent ileal digestible and total amino acid requirements apply to corn and soybean meal–based diets only and have been calculated from standardized ileal digestible amino acid requirements and amino acid contents in corn and dehulled solvent-extracted soybean meal-based diets with 0.1% added lysine·HCl and containing 3% added vitamins and minerals. For each amino acid, dietary levels of corn and soybean meal levels and nutrient requirements were calculated to meet standardized ileal digestible requirements.

TABLE 16-6B Daily Calcium, Phosphorus, and Amino Acid Requirements of Gestating Sows (90% dry matter)[a]

Parity (body weight at breeding, kg)	1 (140)		2 (165)		3 (185)		4 + (205)					
Anticipated gestation weight gain (kg)	65		60		52.2		45		40		45	
Anticipated litter size[b]	12.5		13.5		13.5		13.5		13.5		15.5	
Days of gestation	< 90	> 90	< 90	> 90	< 90	> 90	< 90	> 90	< 90	> 90	< 90	> 90
NE content of the diet (kcal/kg)[a]	2,518	2,518	2,518	2,518	2,518	2,518	2,518	2,518	2,518	2,518	2,518	2,518
Effective DE content of diet (kcal/kg)[a]	3,388	3,388	3,388	3,388	3,388	3,388	3,388	3,388	3,388	3,388	3,388	3,388
Effective ME content of diet (kcal/kg)[a]	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300	3,300
Estimated effective ME intake (kcal/day)	6,678	7,932	6,928	8,182	6,928	8,182	6,897	8,151	6,427	7,681	6,521	7,775
Estimated feed intake + wastage (g/day)[c]	2,130	2,530	2,210	2,610	2,210	2,610	2,200	2,600	2,050	2,450	2,080	2,480
Body weight gain (g/day)	578	543	539	481	472	408	410	340	364	298	416	313
					Calcium and phosphorus (g/day)							
Total calcium	12.42	19.94	11.42	19.31	10.20	17.91	9.05	16.55	8.89	16.40	9.18	17.77
STTD phosphorus[d]	5.40	8.67	4.96	8.39	4.43	7.79	3.93	7.20	3.87	7.13	3.99	7.73
ATTD phosphorus[e,f]	4.61	7.49	4.22	7.25	3.75	6.71	3.30	6.19	3.26	6.15	3.37	6.68
Total phosphorus[f]	9.91	14.78	9.40	14.45	8.67	13.59	7.98	12.75	7.69	12.47	7.89	13.29
					Amino acids[g,h]							
					Standardized ileal digestible basis (g/day)							
Arginine	5.6	8.8	4.8	7.9	4.1	6.9	3.5	6.0	3.2	5.8	3.4	6.2
Histidine	3.7	5.4	3.2	4.8	2.6	4.1	2.2	3.5	2.1	3.3	2.2	3.5
Isoleucine	6.1	8.8	5.3	7.9	4.6	6.9	4.0	5.9	3.7	5.7	3.9	6.1
Leucine	9.6	15.6	8.5	14.2	7.3	12.6	6.4	11.2	6.0	10.8	6.3	11.6
Lysine	**10.6**	**16.7**	**9.2**	**15.1**	**7.8**	**13.1**	**6.7**	**11.5**	**6.3**	**11.1**	**6.6**	**11.9**
Methionine	3.0	4.7	2.6	4.3	2.2	3.7	1.8	3.2	1.7	3.1	1.8	3.4
Methionine + cysteine	6.8	10.8	6.1	10.0	5.4	8.9	4.8	8.1	4.5	7.8	4.7	8.3
Phenylalanine	5.8	9.1	5.1	8.4	4.4	7.4	3.9	6.6	3.7	6.3	3.8	6.8
Phenylalanine + tyrosine	10.1	15.9	9.0	14.5	7.7	12.7	6.7	11.3	6.3	10.9	6.6	11.6
Threonine	7.6	11.5	6.9	10.7	6.2	9.7	5.6	8.8	5.3	8.5	5.4	9.0
Tryptophan	1.9	3.2	1.7	3.0	1.5	2.7	1.4	2.5	1.3	2.4	1.3	2.6
Valine	7.5	11.8	6.7	10.8	5.8	9.5	5.2	8.6	4.9	8.3	5.0	8.8
Total nitrogen	26.8	43.1	24.1	40.1	21.2	36.0	18.9	32.6	17.8	31.5	18.5	33.8
					Apparent ileal digestible basis (g/day)							
Arginine	4.7	7.8	3.9	6.9	3.2	5.8	2.6	4.9	2.4	4.8	2.6	5.2
Histidine	3.4	5.0	2.9	4.4	2.4	3.7	2.0	3.1	1.9	3.0	1.9	3.2
Isoleucine	5.5	8.1	4.8	7.3	4.1	6.2	3.5	5.3	3.3	5.1	3.4	5.5
Leucine	8.7	14.5	7.6	13.1	6.4	11.5	5.5	10.1	5.2	9.8	5.4	10.6
Lysine	**9.9**	**15.8**	**8.5**	**14.1**	**7.1**	**12.21**	**6.0**	**10.6**	**5.6**	**10.2**	**5.9**	**11.0**
Methionine	2.7	4.5	2.3	4.0	1.9	3.4	1.6	3.0	1.5	2.9	1.6	3.1
Methionine + cysteine	6.4	10.2	5.7	9.4	5.0	8.4	4.4	7.6	4.2	7.3	4.3	7.8
Phenylalanine	5.3	8.5	4.6	7.7	3.9	6.7	3.4	5.9	3.2	5.7	3.3	6.2
Phenylalanine + tyrosine	9.4	14.9	8.2	13.5	7.0	11.8	6.0	10.4	5.7	10.0	5.9	10.7
Threonine	6.6	10.3	5.9	9.4	5.2	8.5	4.6	7.6	4.4	7.4	4.5	7.8
Tryptophan	1.6	2.9	1.5	2.7	1.3	2.4	1.1	2.2	1.1	2.2	1.1	2.3
Valine	6.6	10.7	5.8	9.6	5.0	8.5	4.3	7.6	4.1	7.3	4.3	7.8
Total nitrogen	22.7	37.9	20.0	34.9	17.1	30.9	15.0	27.6	14.1	26.8	14.8	28.9

TABLE 16-6B Continued

Parity (body weight at breeding, kg)	1 (140)		2 (165)		3 (185)		4 + (205)					
Anticipated gestation weight gain (kg)	65		60		52.2		45		40		45	
Anticipated litter size[b]	12.5		13.5		13.5		13.5		13.5		15.5	
Days of gestation	< 90	> 90	< 90	> 90	< 90	> 90	< 90	> 90	< 90	> 90	< 90	> 90
	Total basis (g/day)											
Arginine	6.5	10.0	5.7	9.1	4.9	8.0	4.3	7.1	4.0	6.8	4.2	7.3
Histidine	4.4	6.4	3.9	5.7	3.3	5.0	2.9	4.3	2.7	4.1	2.8	4.4
Isoleucine	7.2	10.3	6.4	9.4	5.6	8.2	4.9	7.2	4.6	6.9	4.8	7.4
Leucine	11.1	17.9	9.9	16.5	8.5	14.6	7.5	13.0	7.1	12.6	7.4	13.5
Lysine	**12.4**	**19.3**	**11.0**	**17.5**	**9.4**	**15.4**	**8.2**	**13.6**	**7.7**	**13.1**	**8.0**	**14.0**
Methionine	3.6	5.6	3.1	5.1	2.7	4.5	2.4	3.9	2.2	3.8	2.3	4.1
Methionine + cysteine	8.3	12.9	7.5	12.0	6.7	10.8	6.0	9.8	5.7	9.5	5.9	10.1
Phenylalanine	6.9	10.7	6.1	9.8	5.3	8.7	4.7	7.8	4.5	7.5	4.6	8.0
Phenylalanine + tyrosine	12.3	18.9	11.0	17.4	9.6	15.4	8.5	13.8	8.0	13.3	8.3	14.1
Threonine	9.4	14.0	8.6	13.2	7.8	12.0	7.1	10.9	6.7	10.5	6.9	11.1
Tryptophan	2.2	3.6	2.0	3.4	1.8	3.1	1.6	2.9	1.6	2.8	1.6	3.0
Valine	9.0	14.0	8.1	12.9	7.2	11.5	6.4	10.4	6.0	10.0	6.2	10.65
Total nitrogen	32.7	51.7	29.8	48.4	26.5	43.8	23.9	39.9	22.5	38.5	23.3	41.1

[a]Dietary energy contents relate to corn and soybean meal–based diets. Effective DE and effective ME contents are calculated from NE contents using fixed conversion values for sows. For corn and soybean meal–based diets, effective DE and effective ME contents are similar to actual DE and ME contents. The optimum dietary energy content varies with availability and costs of local feed ingredients. When using alternative feed ingredients, it is suggested that diets be formulated based on NE contents and nutrient requirements be adjusted to maintain constant nutrient-to-net energy ratios.

[b]Anticipated mean birth weight 1.40 kg.

[c]Assumes 5% feed wastage.

[d]Standardized total tract digestible.

[e]Apparent total tract digestible.

[f]Apparent total tract digestible and total phosphorus requirements apply to corn and soybean meal–based diets only and have been calculated from standardized total tract digestible phosphorus requirements and nutrient profiles in corn, dehulled solvent-extracted soybean meal, and dicalcium phosphate. Diets were assumed to contain 0.1% added lysine·HCl and 3% added vitamins and minerals. Corn and soybean meal levels were calculated to meet standardized ileal digestible lysine requirements, and dicalcium phosphate amounts were varied to meet requirements for standardized total tract digestible phosphorus.

[g]The requirements are estimated from the growth model.

[h]Apparent ileal digestible and total amino acid requirements apply to corn and soybean meal–based diets only and have been calculated from standardized ileal digestible amino acid requirements and amino acid contents in corn and dehulled solvent-extracted soybean meal–based diets with 0.1% added lysine·HCl and containing 3% added vitamins and minerals. For each amino acid, dietary levels of corn and soybean meal levels and nutrient requirements were calculated to meet standardized ileal digestible requirements.

TABLE 16-7A Dietary Calcium, Phosphorus, and Amino Acid Requirements of Lactating Sows (90% dry matter)[a]

Parity	1			2 +		
Postfarrowing body weight (kg)	175	175	175	210	210	210
Litter size	11	11	11	11.5	11.5	11.5
Lactation length (days)	21	21	21	21	21	21
Mean daily weight gain of nursing pigs (g)	190	230	270	190	230	270
NE content of the diet (kcal/kg)[a]	2,518	2,518	2,518	2,518	2,518	2,518
Effective DE content of diet (kcal/kg)[a]	3,388	3,388	3,388	3,388	3,388	3,388
Effective ME content of diet (kcal/kg)[a]	3,300	3,300	3,300	3,300	3,300	3,300
Estimated effective ME intake (Mcal/day)	18.7	18.7	18.7	20.7	20.7	20.7
Estimated feed intake + wastage (g/day)[b]	5.95	5.95	5.93	6.61	6.61	6.61
Anticipated sow body weight change (kg)	1.5	–7.7	–17.4	3.7	–5.8	–15.9
	Calcium and phosphorus (%)					
Total calcium	0.63	0.71	0.80	0.60	0.68	0.76
STTD phosphorus[c]	0.31	0.36	0.40	0.30	0.34	0.38
ATTD phosphorus[d,e]	0.27	0.31	0.35	0.26	0.29	0.33
Total phosphorus[e]	0.56	0.62	0.67	0.54	0.60	0.65
	Amino acids[f,g]					
	Standardized ileal digestible basis (%)					
Arginine	0.43	0.44	0.46	0.42	0.43	0.45
Histidine	0.30	0.32	0.34	0.29	0.31	0.33
Isoleucine	0.41	0.45	0.49	0.40	0.43	0.47
Leucine	0.83	0.92	1.00	0.80	0.88	0.96
Lysine	**0.75**	**0.81**	**0.87**	**0.72**	**0.78**	**0.84**
Methionine	0.20	0.21	0.23	0.19	0.21	0.22
Methionine + cysteine	0.39	0.43	0.47	0.38	0.41	0.45
Phenylalanine	0.41	0.44	0.48	0.39	0.42	0.46
Phenylalanine + tyrosine	0.83	0.91	0.99	0.80	0.87	0.95
Threonine	0.47	0.51	0.55	0.46	0.49	0.53
Tryptophan	0.14	0.15	0.17	0.13	0.15	0.16
Valine	0.64	0.69	0.74	0.61	0.66	0.71
Total nitrogen	1.62	1.73	1.86	1.56	1.67	1.79
	Apparent ileal digestible basis (%)					
Arginine	0.39	0.40	0.41	0.38	0.39	0.40
Histidine	0.28	0.30	0.33	0.27	0.29	0.31
Isoleucine	0.39	0.42	0.46	0.37	0.41	0.44
Leucine	0.79	0.87	0.95	0.76	0.83	0.91
Lysine	**0.71**	**0.77**	**0.83**	**0.68**	**0.74**	**0.80**
Methionine	0.19	0.20	0.22	0.18	0.20	0.21
Methionine + cysteine	0.37	0.41	0.44	0.36	0.39	0.42
Phenylalanine	0.38	0.41	0.45	0.36	0.40	0.43
Phenylalanine + tyrosine	0.78	0.86	0.95	0.75	0.83	0.90
Threonine	0.42	0.46	0.50	0.41	0.44	0.48
Tryptophan	0.13	0.14	0.16	0.12	0.14	0.15
Valine	0.58	0.64	0.69	0.56	0.61	0.66
Total nitrogen	1.40	1.52	1.64	1.35	1.46	1.57

TABLE 16-7A Continued

Parity	1			2 +		
Postfarrowing body weight (kg)	175	175	175	210	210	210
Litter size	11	11	11	11.5	11.5	11.5
Lactation length (days)	21	21	21	21	21	21
Mean daily weight gain of nursing pigs (g)	190	230	270	190	230	270
			Total basis (%)			
Arginine	0.48	0.50	0.51	0.47	0.48	0.50
Histidine	0.35	0.37	0.40	0.34	0.36	0.38
Isoleucine	0.49	0.52	0.56	0.47	0.50	0.54
Leucine	0.96	1.05	1.15	0.92	1.01	1.10
Lysine	**0.86**	**0.93**	**1.00**	**0.83**	**0.90**	**0.96**
Methionine	0.23	0.25	0.27	0.23	0.24	0.26
Methionine + cysteine	0.47	0.51	0.55	0.46	0.49	0.53
Phenylalanine	0.47	0.51	0.55	0.46	0.49	0.53
Phenylalanine + tyrosine	0.98	1.07	1.16	0.94	1.03	1.12
Threonine	0.58	0.62	0.67	0.56	0.60	0.65
Tryptophan	0.16	0.18	0.19	0.15	0.17	0.18
Valine	0.75	0.81	0.87	0.72	0.78	0.84
Total nitrogen	1.95	2.08	2.22	1.89	2.01	2.15

[a]Dietary energy contents relate to corn and soybean meal–based diets. Effective DE and effective ME contents are calculated from NE contents using fixed conversion values for sows. For corn and soybean meal–based diets, effective DE and effective ME contents are similar to actual DE and ME contents. The optimum dietary energy content varies with availability and costs of local feed ingredients. When using alternative feed ingredients, it is suggested that diets be formulated based on NE contents and nutrient requirements be adjusted to maintain constant nutrient-to-net energy ratios.

[b]Assumes 5% feed wastage.

[c]Standardized total tract digestible.

[d]Apparent total tract digestible.

[e]Apparent total tract digestible and total phosphorus requirements apply to corn and soybean meal–based diets only and have been calculated from standardized total tract digestible phosphorus requirements and nutrient profiles in corn, dehulled solvent-extracted soybean meal, and dicalcium phosphate. Diets were assumed to contain 0.1% added lysine·HCl and 3% added vitamins and minerals. Corn and soybean meal levels were calculated to meet standardized ileal digestible lysine requirements, and dicalcium phosphate amounts were varied to meet requirements for standardized total tract digestible phosphorus.

[f]The requirements are estimated from the growth model.

[g]Apparent ileal digestible and total amino acid requirements apply to corn and soybean meal–based diets only and have been calculated from standardized ileal digestible amino acid requirements and amino acid contents in corn and dehulled solvent-extracted soybean meal–based diets with 0.1% added lysine·HCl and containing 3% added vitamins and minerals. For each amino acid, dietary levels of corn and soybean meal levels and nutrient requirements were calculated to meet standardized ileal digestible requirements.

TABLE 16-7B Daily Calcium, Phosphorus, and Amino Acid Requirements of Lactating Sows (90% dry matter)

Parity	1			2 +		
Postfarrowing body weight (kg)	175	175	175	210	210	210
Litter size	11	11	11	11.5	11.5	11.5
Lactation length (days)	21	21	21	21	21	21
Mean daily weight gain of nursing pigs (g)	190	230	270	190	230	270
NE content of the diet (kcal/kg)[a]	2,518	2,518	2,518	2,518	2,518	2,518
Effective DE content of diet (kcal/kg)[a]	3,388	3,388	3,388	3,388	3,388	3,388
Effective ME content of diet (kcal/kg)[a]	3,300	3,300	3,300	3,300	3,300	3,300
Estimated effective ME intake (Mcal/day)	18.7	18.7	18.7	20.7	20.7	20.7
Estimated feed intake + wastage (g/day)[b]	5.95	5.95	5.93	6.61	6.61	6.61
Anticipated sow body weight change (kg)	1.5	–7.7	–17.4	3.7	–5.8	–15.9
	Calcium and phosphorus (g/day)					
Total calcium	35.3	40.3	45.0	37.7	42.9	48.1
STTD phosphorus[c]	17.7	20.1	22.6	18.9	21.4	24.0
ATTD phosphorus[d,e]	15.1	17.3	19.6	16.1	18.4	20.8
Total phosphorus[e]	31.6	34.8	38.1	34.1	37.4	40.8
	Amino acids[f,g]					
	Standardized ileal digestible basis (g/day)					
Arginine	24.3	25.1	26.0	26.3	27.1	28.0
Histidine	16.9	18.2	19.5	18.1	19.4	20.8
Isoleucine	23.4	25.5	27.5	25.1	27.2	29.4
Leucine	47.1	51.9	56.7	50.3	55.2	60.3
Lysine	**42.2**	**45.7**	**49.3**	**45.3**	**48.9**	**52.6**
Methionine	11.3	12.2	13.1	12.1	13.0	14.0
Methionine + cysteine	22.3	24.3	26.4	23.8	26.0	28.1
Phenylalanine	22.9	24.9	27.0	24.5	26.6	28.8
Phenylalanine + tyrosine	46.9	51.6	56.3	50.1	55.0	59.9
Threonine	26.8	29.0	31.3	28.8	31.1	33.5
Tryptophan	7.9	8.7	9.6	8.4	9.3	10.2
Valine	35.9	38.9	42.0	38.5	41.6	44.9
Total nitrogen	91.1	98.1	105.2	97.9	105.1	112.5
	Apparent ileal digestible basis (g/day)					
Arginine	21.8	22.6	23.5	23.6	24.4	25.2
Histidine	15.9	17.2	18.5	17.1	18.4	19.7
Isoleucine	21.9	23.9	26.0	23.4	25.5	27.7
Leucine	44.5	49.2	54.0	47.4	52.3	57.3
Lysine	**40.0**	**43.5**	**47.0**	**42.9**	**46.5**	**50.1**
Methionine	10.7	11.6	12.5	11.4	12.3	13.3
Methionine + cysteine	21.0	22.9	24.9	22.4	24.5	26.6
Phenylalanine	21.3	23.3	25.4	22.8	24.9	27.0
Phenylalanine + tyrosine	44.3	48.9	53.5	47.2	52.0	56.8
Threonine	23.8	26.0	28.1	25.5	27.7	30.0
Tryptophan	7.2	8.1	8.9	7.7	8.5	9.4
Valine	33.0	36.0	39.0	35.4	38.4	41.6
Total nitrogen	79.2	85.9	92.8	84.8	91.7	98.9

TABLE 16-7B Continued

Parity	1			2 +		
Postfarrowing body weight (kg)	175	175	175	210	210	210
Litter size	11	11	11	11.5	11.5	11.5
Lactation length (days)	21	21	21	21	21	21
Mean daily weight gain of nursing pigs (g)	190	230	270	190	230	270
	Total basis (g/day)					
Arginine	27.3	28.2	29.1	29.6	30.5	31.4
Histidine	19.7	21.1	22.5	21.1	22.6	24.1
Isoleucine	27.4	29.6	31.9	29.4	31.7	34.1
Leucine	54.1	59.5	65.0	57.8	63.4	69.1
Lysine	**48.7**	**52.6**	**56.5**	**52.4**	**56.4**	**60.5**
Methionine	13.2	14.2	15.1	14.2	15.2	16.2
Methionine + cysteine	26.7	29.0	31.3	28.7	31.1	33.5
Phenylalanine	26.7	29.0	31.3	28.6	31.0	33.4
Phenylalanine + tyrosine	55.3	60.5	65.8	59.1	64.6	70.2
Threonine	32.7	35.3	37.9	35.2	37.9	40.6
Tryptophan	9.0	9.9	10.9	9.6	10.6	11.6
Valine	42.2	45.7	49.2	45.3	48.9	52.5
Total nitrogen	109.9	117.8	125.8	118.4	126.5	134.9

[a]Dietary energy contents relate to corn and soybean meal–based diets. Effective DE and effective ME contents are calculated from NE contents using fixed conversion values for sows. For corn and soybean meal–based diets, effective DE and effective ME contents are similar to actual DE and ME contents. The optimum dietary energy content varies with availability and costs of local feed ingredients. When using alternative feed ingredients, it is suggested that diets be formulated based on NE contents and nutrient requirements be adjusted to maintain constant nutrient-to-net energy ratios.

[b]Assumes 5% feed wastage.

[c]Standardized total tract digestible.

[d]Apparent total tract digestible.

[e]Apparent total tract digestible and total phosphorus requirements apply to corn and soybean meal–based diets only and have been calculated from standardized total tract digestible phosphorus requirements and nutrient profiles in corn, dehulled solvent-extracted soybean meal, and dicalcium phosphate. Diets were assumed to contain 0.1% added lysine·HCl and 3% added vitamins and minerals. Corn and soybean meal levels were calculated to meet standardized ileal digestible lysine requirements, and dicalcium phosphate amounts were varied to meet requirements for standardized total tract digestible phosphorus.

[f]The requirements are estimated from the growth model.

[g]Apparent ileal digestible and total amino acid requirements apply to corn and soybean meal–based diets only and have been calculated from standardized ileal digestible amino acid requirements and amino acid contents in corn and dehulled solvent-extracted soybean meal–based diets with 0.1% added lysine·HCl and containing 3% added vitamins and minerals. For each amino acid, dietary levels of corn and soybean meal levels and nutrient requirements were calculated to meet standardized ileal digestible requirements.

TABLE 16-8A Dietary Mineral, Vitamin, and Fatty Acid Requirements of Gestating and Lactating Sows (90% dry matter)

Item	Gestation	Lactation
NE content of the diet (kcal/kg)[a]	2,518	2,518
Effective DE content of diet (kcal/kg)[a]	3,388	3,388
Effective ME content of diet (kcal/kg)[a]	3,300	3,300
Estimated effective ME intake (kcal/day)	6,928	19,700
Estimated feed intake + wastage (g/day)[b]	2,210	6,280
	Requirements (% or amount/kg of diet)	
Mineral elements		
Sodium (%)	0.15	0.20
Chlorine (%)	0.12	0.16
Magnesium (%)	0.06	0.06
Potassium (%)	0.20	0.20
Copper (mg/kg)	10	20
Iodine (mg/kg)	0.14	0.14
Iron (mg/kg)	80	80
Manganese (mg/kg)	25	25
Selenium (mg/kg)	0.15	0.15
Zinc (mg/kg)	100	100
Vitamins		
Vitamin A (IU/kg)[c]	4,000	2,000
Vitamin D_3 (IU/kg)[d]	800	800
Vitamin E (IU/kg)[e]	44	44
Vitamin K (menadione) (mg/kg)	0.50	0.50
Biotin (mg/kg)	0.20	0.20
Choline (g/kg)	1.25	1.00
Folacin (mg/kg)	1.30	1.30
Niacin, available (mg/kg)[f]	10	10
Pantothenic acid (mg/kg)	12	12
Riboflavin (mg/kg)	3.75	3.75
Thiamin (mg/kg)	1.00	1.00
Vitamin B_6 (mg/kg)	1.00	1.00
Vitamin B_{12} (µg/kg)	15	15
Linoleic acid (%)	0.10	0.10

[a]Dietary energy contents relate to corn and soybean meal–based diets. Effective DE and effective ME contents are calculated from NE contents using fixed conversion values for sows. For corn and soybean meal–based diets, effective DE and effective ME contents are similar to actual DE and ME contents. The optimum dietary energy content varies with availability and costs of local feed ingredients. When using alternative feed ingredients, it is suggested that diets be formulated based on NE contents and nutrient requirements be adjusted to maintain constant nutrient-to-net energy ratios.

[b]Assumes 5% feed wastage.

[c]1 IU vitamin A = 0.30 µg retinol or 0.344 µg retinyl acetate. Vitamin A activity (also known as retinol equivalents) is also provided by β-carotene (see Vitamins chapter).

[d]1 IU vitamin D_2 or D_3 = 0.025 µg

[e]1 IU vitamin E = 0.67 mg of D-α-tocopherol or 1 mg of DL-α-tocopheryl acetate. Recent research with swine has shown a substantial difference in the activity of natural and synthetic α-tocopheryl acetates (see Vitamins chapter).

[f]The niacin in corn, grain sorghum, wheat, and barley is unavailable. Similarly, the niacin in byproducts made from these cereal grains is poorly available unless the byproducts have undergone fermentation of wet-milling process.

TABLE 16-8B Daily Mineral, Vitamin, and Fatty Acid Requirements of Gestating and Lactating Sows (90% dry matter)

Item	Gestation	Lactation
NE content of the diet (kcal/kg)[a]	2,518	2,518
Effective DE content of diet (kcal/kg)[a]	3,388	3,388
Effective ME content of diet (kcal/kg)[a]	3,300	3,300
Estimated effective ME intake (kcal/day)	6,928	19,700
Estimated feed intake + wastage (g/day)[b]	2,210	6,280
	Requirements (amount/day)	
Mineral elements		
Sodium (g)	3.15	11.93
Chlorine (g)	2.52	9.55
Magnesium (g)	1.26	3.58
Potassium (g)	4.20	11.93
Copper (mg)	21.00	119.32
Iodine (mg)	0.29	0.84
Iron (mg)	168.0	477.3
Manganese (mg)	52.49	149.15
Selenium (mg)	0.31	0.89
Zinc (mg)	210.0	596.6
Vitamins		
Vitamin A (IU)[c]	8,398	11,932
Vitamin D_3 (IU)[d]	1,680	4,773
Vitamin E (IU)[e]	92.4	262.5
Vitamin K (menadione) (mg)	1.05	2.98
Biotin (mg)	0.42	1.19
Choline (g)	2.62	5.97
Folacin (mg)	2.73	7.76
Niacin, available (mg)[f]	21.00	59.66
Pantothenic acid (mg)	25.19	71.59
Riboflavin (mg)	7.87	22.37
Thiamin (mg)	2.10	5.97
Vitamin B_6 (mg)	2.10	5.97
Vitamin B_{12} (µg)	31.49	89.49
Linoleic acid (g)	2.1	6.0

[a]Dietary energy contents relate to corn and soybean meal–based diets. Effective DE and effective ME contents are calculated from NE contents using fixed conversion values for sows. For corn and soybean meal–based diets, effective DE and effective ME contents are similar to actual DE and ME contents. The optimum dietary energy content varies with availability and costs of local feed ingredients. When using alternative feed ingredients, it is suggested that diets be formulated based on NE contents and nutrient requirements be adjusted to maintain constant nutrient-to-net energy ratios.

[b]Assumes 5% feed wastage.

[c]1 IU vitamin A = 0.30 µg retinol or 0.344 µg retinyl acetate. Vitamin A activity (also known as retinol equivalents) is also provided by β-carotene (see Vitamins chapter).

[d]1 IU vitamin D_2 or D_3 = 0.025 µg

[e]1 IU vitamin E = 0.67 mg of D-α-tocopherol or 1 mg of DL-α-tocopheryl acetate. Recent research with swine has shown a substantial difference in the activity of natural and synthetic α-tocopheryl acetates (see Vitamins chapter).

[f]The niacin in corn, grain sorghum, wheat, and barley is unavailable. Similarly, the niacin in byproducts made from these cereal grains is poorly available unless the byproducts have undergone fermentation of wet-milling process.

TABLE 16-9 Dietary and Daily Amino Acid, Mineral, Vitamin, and Fatty Acid Requirements of Sexually Active Boars (90% dry matter)[a]

NE content of the diet (kcal/kg)[b]	2,475
Effective DE content of diet (kcal/kg)[b]	3,402
Effective ME content of diet (kcal/kg)[b]	3,300
Estimated effective ME intake (kcal/day)[b]	7,838
Estimated feed intake + wastage (g/day)[c]	2,500

	Requirements	
	% or amount/kg of diet	Amount/day
Amino acids (standardized ileal digestible basis)		
Arginine	0.20%	4.86 g
Histidine	0.15%	3.46 g
Isoleucine	0.31%	7.41 g
Leucine	0.33%	7.83 g
Lysine	**0.51%**	**11.99 g**
Methionine	0.08%	1.96 g
Methionine + cysteine	0.25%	5.98 g
Phenylalanine	0.36%	8.50 g
Phenylalanine + tyrosine	0.58%	13.77 g
Threonine	0.22%	5.19 g
Tryptophan	0.20%	4.82 g
Valine	0.27%	6.52 g
Total nitrogen	1.14%	27.04 g
Amino acids (apparent ileal digestible basis)[d]		
Arginine	0.16%	3.86 g
Histidine	0.13%	3.16 g
Isoleucine	0.29%	6.81 g
Leucine	0.29%	6.84 g
Lysine	**0.47%**	**11.13 g**
Methionine	0.07%	1.72 g
Methionine + cysteine	0.23%	5.55 g
Phenylalanine	0.33%	7.86 g
Phenylalanine + tyrosine	0.54%	12.81 g
Threonine	0.17%	4.15 g
Tryptophan	0.19%	4.52 g
Valine	0.23%	5.58 g
Total nitrogen	0.94%	22.40 g
Amino acids (total basis)[d]		
Arginine	0.25%	5.83 g
Histidine	0.18%	4.30 g
Isoleucine	0.37%	8.81 g
Leucine	0.39%	9.20 g
Lysine	**0.60%**	**14.25 g**
Methionine	0.11%	2.55 g
Methionine + cysteine	0.31%	7.44 g
Phenylalanine	0.42%	9.96 g
Phenylalanine + tyrosine	0.70%	16.55 g
Threonine	0.28%	6.70 g
Tryptophan	0.23%	5.42 g
Valine	0.34%	8.01 g
Total nitrogen	1.41%	33.48 g

continued

TABLE 16-9 Continued

	Requirements % or amount/kg of diet	Requirements Amount/day
Mineral elements		
Total calcium	0.75%	17.81 g
STTD phosphorus[e]	0.33%	7.84 g
ATTD phosphorus[f,g]	0.31%	7.36 g
Total phosphorus[g]	0.75%	17.81 g
Sodium	0.15%	3.56 g
Chlorine	0.12%	2.85 g
Magnesium	0.04%	0.95 g
Potassium	0.20%	4.75 g
Copper	5 mg	11.88 mg
Iodine	0.14 mg	0.33 mg
Iron	80 mg	190 mg
Manganese	20 mg	47.5 mg
Selenium	0.30 mg	0.71 mg
Zinc	50 mg	118.75 mg
Vitamins		
Vitamin A[h]	4,000 IU	9,500 IU
Vitamin D_3[i]	200 IU	475 IU
Vitamin E[j]	44 IU	104.5 IU
Vitamin K (menadione)	0.50 mg	1.19 mg
Biotin	0.20 mg	0.48 mg
Choline	1.25 g	2.97 g
Folacin	1.30 mg	3.09 mg
Niacin, available[k]	10 mg	23.75 mg
Pantothenic acid	12 mg	28.50 mg
Riboflavin	3.75 mg	8.91 mg
Thiamin	1.0 mg	2.38 mg
Vitamin B_6	1.0 mg	2.38 mg
Vitamin B_{12}	15 µg	35.63 µg
Linoleic acid	0.1%	2.38%

[a]The requirements are based on daily feed intake plus wastage of 2.5 kg of feed. Feed intake may need to be adjusted, depending on the weight of the boar and the amount of weight gain desired.

[b]Dietary energy contents relate to corn and soybean meal–based diets. Effective DE and effective ME contents are calculated from NE contents using fixed conversion values for pigs below and above 25 kg body weight. For corn and soybean meal–based diets, effective DE and effective ME contents are similar to actual DE and ME contents. The optimum dietary energy content varies with availability and costs of local feed ingredients. When using alternative feed ingredients, it is suggested that diets be formulated based on NE contents and nutrient requirements be adjusted to maintain constant nutrient-to-net energy ratios.

[c]Assumes 5% feed wastage.

[d]Apparent ileal digestible and total amino acid requirements apply to corn and soybean meal–based diets only and have been calculated from standardized ileal digestible amino acid requirements and amino acid contents in corn and dehulled solvent-extracted soybean meal–based diets with 0.1% added lysine·HCl and containing 3% added vitamins and minerals. For each amino acid, dietary levels of corn and soybean meal levels and nutrient requirements were calculated to meet standardized ileal digestible requirements.

[e]Standardized total tract digestible.

[f]Apparent total tract digestible.

[g]Apparent total tract digestible and total phosphorus requirements apply to corn and soybean meal–based diets only and have been calculated from standardized total tract digestible phosphorus requirements and nutrient profiles in corn, dehulled solvent-extracted soybean meal, and dicalcium phosphate. Diets were assumed to contain 0.1% added lysine·HCl and 3% added vitamins and minerals. Corn and soybean meal levels were calculated to meet standardized ileal digestible lysine requirements, and dicalcium phosphate amounts were varied to meet requirements for standardized total tract digestible phosphorus.

[h]1 IU vitamin A = 0.30 µg retinol or 0.344 µg retinyl acetate. Vitamin A activity (also known as retinol equivalents) is also provided by β-carotene (see Vitamins chapter).

[i]1 IU vitamin D_2 or D_3 = 0.025 µg

[j]1 IU vitamin E = 0.67 mg of D-α-tocopherol or 1 mg of DL-α-tocopheryl acetate. Recent research with swine has shown a substantial difference in the activity of natural and synthetic α-tocopheryl acetates (see Vitamins chapter).

[k]The niacin in corn, grain sorghum, wheat, and barley is unavailable. Similarly, the niacin in byproducts made from these cereal grains is poorly available unless the byproducts have undergone fermentation of wet-milling process.

17

Feed Ingredient Composition

INTRODUCTION

The composition of feed ingredients is presented in Table 17-1. All data are presented on an "as-fed" basis. The presentation of the nutrient and proximate composition of ingredients differs from that of previous editions of the *Nutrient Requirements of Swine*. In this edition, each ingredient is presented on an individual page. This method of presentation was selected to facilitate ease of use because in most, if not all, diet formulation programs, all the nutrients/proximate components of an ingredient are added at once and not as individual or groups of nutrient/proximate components. The name of the ingredient, its number as designated by the Association of Feed Control Officials (AAFCO, 2010), the page number in AAFCO (2010) where the description of the ingredient is located, and the International Feed Number (IFN) are included where this information was available. In some instances, a brief description of the ingredient was included if it deviated from the AAFCO (2010) description or if no description was provided by AAFCO.

The committee conducted an exhaustive review of the literature to arrive at the nutrient/proximate composition of each ingredient. For the total composition of nutrient/proximate components, the review of literature focused on the last 15 years. For apparent and standardized ileal digestibility of amino acids and apparent and standardized total tract digestibility of phosphorus, the time of publication was not considered and an attempt was made to locate every publication that contained these data. A brief explanation of each of the components of the ingredient composition table is presented below.

For all nutrients, if the number of observations is included along with a standard deviation variation (if the number of observations is greater than one), then the information is based on the committee's review of the literature. If the number of observations is not presented, then the information was obtained from other summarized sources (NRC, 1998, 2007; Sauvant et al., 2004; CVB, 2008; AminoDat, 2010).

Although it is recognized that the nutrient composition of some crops varies considerably, depending on the geographic region in which they are produced, the committee did not find a sufficient amount of data to make distinctions in these tables. Other databases, such as that compiled by the International Life Sciences Institute (https://www.cropcomposition.org), contain a large amount of data on geographic effects for a few major crops.

PROXIMATE COMPONENTS AND CARBOHYDRATES

The information contained in this section of Table 17-1 is almost exclusively from the committee's review of the literature with the following exceptions. The information for starch and acid detergent fiber came from either the committee's review or from other summarized data. Other summarized data were used for these components when necessary because these data were used to calculate net energy (NE; Chapter 1). A value for ether extract is presented in this section, and an ether extract value also is presented in the fatty acids section as described below. Although the laboratory methodology was not always clear in the published literature, we assumed ether extract values were derived from petroleum ether extraction, and acid ether extract refers to acid hydrolysis. Crude fiber is included in the list of proximate components. Although it is widely accepted that crude fiber has little theoretical or practical value in swine nutrition, it is still used in various parts of the world and is included on feed labels in the United States.

AMINO ACIDS

The amino acid content expressed on a total basis is entirely from the committee's review of the literature or from the National Research Council (NRC, 1998). The apparent digestibility of amino acids is from the committee's review of the literature or from other summarized sources. If the literature search produced three or fewer observations for apparent digestibility of amino acids, the data were compared to NRC (1998) or CVB (2008). If the committee's data, regardless of the number of observations, were in close agreement with those other sources, we used the data from the literature review. However, if there were three or fewer observations, and the data from the review of literature were not in close agreement with NRC (1998) or CVB, we used data from NRC (1998). If no data were available from NRC (1998), we used data from CVB. An identical procedure was used for standardized ileal digestibility with the exception that comparisons were made among NRC (1998), Sauvant et al., (2004), CVB (2008), and AminoDat (2010). Where there were no observations, the data available from the summarized sources were averaged. For select ingredient groups, such as the corn coproducts (Chapter 9) the average digestible value for all ingredients in a group was used for each individual ingredient in the group, which will be obvious in the table.

MINERALS

The total concentration of minerals came from the committee's review of the literature or from NRC (1998). The microminerals are almost exclusively from NRC (1998). The apparent and standardized total tract digestibilites of phosphorus were exclusively from the committee's review of the literature, and were calculated as described in Chapter 13. The mineral content of several macromineral sources is presented in Table 17-2, taken, with minor edits, from NRC (1998). Table 17-3, also from NRC (1998), lists sources and bioavailabilities of trace minerals.

VITAMINS

The concentration of vitamins is almost exclusively from NRC (1998).

FATTY ACIDS

The concentrations of fatty acid data were obtained from Sauvant et al. (2004) or from the U.S. Department of Agriculture (USDA, 2010). The fatty acids are presented as a percentage of ether extract. The ether extract value came from the same source as the fatty acids, and this value was not always identical to the value in the proximate components from the committee's review. Iodine value and iodine value product were calculated as described in Chapter 3. Characteristics and energy values of various sources of fats and oils are listed in Table 17-4.

ENERGY

Gross energy data are from the committee's review or NRC (1998). Digestible energy data are from the committee's review, NRC (1998), or Sauvant et al., (2004). Net energy was calculated as described in Chapter 1.

LIST OF INGREDIENTS

The following ingredients are listed in Table 17-1.

1	Alfalfa Hay
2	Alfalfa Meal
3	Bakery Meal
4	Barley
5	Barley, Hulless
6	Beans, Faba
7	Beans, Phaselous Beans
8	Blood Cells
9	Blood Meal
10	Blood Plasma
11	Brewers Grains
12	Camelina Meal
13	Canola, Full Fat
14	Canola Meal, Expelled
15	Canola Meal, Solvent Extracted
16	Cassava Meal
17	Citrus Pulp
18	Copra Expelled
19	Copra Meal
20	Corn, Yellow Dent
21	Corn, Nutridense
22	Corn Bran
23	Corn DDG
24	Corn DDGS, > 10% Oil
25	Corn DDGS, > 6 and < 9% Oil
26	Corn DDGS, < 4% Oil
27	Corn HP DDG
28	Corn Distillers Solubles
29	Corn Germ
30	Corn Germ Meal
31	Corn Gluten Feed
32	Corn Gluten Meal
33	Corn Grits, Hominy Feed
34	Cottonseed, Full Fat
35	Cottonseed Meal
36	Egg, Whole, Spray Dried
37	Feather Meal
38	Fish Meal, Combined
39	Flaxseed
40	Flaxseed Meal
41	Gelatin
42	Kidney Beans, Extruded
43	Kidney Beans, Raw
44	Lentils
45	Lupins
46	Meat and Bone Meal, P > 4%
47	Meat Meal

48 Milk, Casein
49 Milk, Lactose
50 Milk, Skim Milk Powder
51 Milk, Whey Permeate, 80% Lactose
52 Milk, Whey Permeate, 85% Lactose
53 Milk, Whey Powder
54 Milk, Whey Protein Concentrate
55 Millet
56 Molasses, Sugar Beets
57 Molasses, Sugar Cane
58 Oat Groats
59 Oats
60 Oats, Naked
61 Oats, Rolled, Dehulled
62 Palm Kernel Expelled
63 Palm Kernel Meal
64 Peanut Meal, Expelled
65 Peanut Meal, Extracted
66 Pea Protein Concentrate
67 Peas, Chick Peas
68 Peas, Cow Peas
69 Peas, Field Peas
70 Peas, Field Pea Splits
71 Pet Food Byproduct
72 Porcine Solubles, Dried
73 Potato Protein Concentrate
74 Poultry Byproduct
75 Poultry Meal
76 Rice
77 Rice Bran
78 Rice Bran, Defatted
79 Rice, Broken
80 Rice, Polished
81 Rice Protein Concentrate
82 Rye
83 Safflower Meal
84 Safflower Meal, Dehulled
85 Salmon Protein Hydrolysate
86 Sesame Meal
87 Sorghum
88 Sorghum, DDGS
89 Soybean Hulls
90 Soybean Meal, Dehulled, Expelled
91 Soybean Meal, Dehulled, Solvent Extracted
92 Soybean Meal, Enzyme Treated
93 Soybean Meal, Expelled
94 Soybean Meal, Fermented
95 Soybean Meal, High Protein, Dehulled, Solvent Extracted
96 Soybean Meal, High Protein, Expelled
97 Soybean Meal, Low Oligosaccharide, Dehulled, Solvent Extracted
98 Soybean Meal, Low Oligosaccharide, Expelled
99 Soybean Meal, Solvent Extracted
100 Soybeans, Full Fat
101 Soybeans, High Protein, Full Fat
102 Soybeans, Low Oligosaccharide, Full Fat
103 Soy Protein Concentrate
104 Soy Protein Isolate
105 Sugar Beet Pulp
106 Sunflower, Full Fat
107 Sunflower Meal, Dehulled, Solvent Extracted
108 Sunflower Meal, Solvent Extracted
109 Triticale
110 Triticale DDGS
111 Wheat, Hard Red
112 Wheat, Soft Red
113 Wheat Bran
114 Wheat DDGS
115 Wheat Gluten
116 Wheat Middlings
117 Wheat Screenings
118 Wheat Shorts
119 Yeast, Brewers'
120 Yeast, Ethanol
121 Yeast, Single Cell Protein
122 Yeast, Torula

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TABLE 17-1 Composition of Feed Ingredients Used in Swine Diets (data on as-fed basis)

Ingredient: Alfalfa Hay
AAFCO #: 3.1, AAFCO 2010, p. 324
IFN #: 1-30-293

Proximate Components, %

	x̄	n	SD
Dry matter	90.33	3	0.61
Crude protein	19.32	7	3.47
Crude fiber			
Ether extract	2.30	6	0.63
Acid ether extract			
Ash	11.00	6	2.33

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	1.02	1	
Neutral detergent fiber	37.00	7	7.50
Acid detergent fiber	31.01	7	7.95
Hemicellulose			
Acid detergent lignin	6.65	1	
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	19.32	7	3.47						
Arg									
His									
Ile									
Leu									
Lys									
Met									
Phe									
Thr									
Trp									
Val									
Nonessential									
Ala									
Asp									
Cys									
Glu									
Gly									
Pro									
Ser									
Tyr									

Minerals

	x̄	n	SD
Macro, %			
Ca	1.46	8	0.29
Cl			
K	2.48	4	0.75
Mg	0.27	5	0.04
Na	0.02	1	
P	0.26	8	0.07
S	0.28	2	0.01
Micro, ppm			
Cr			
Cu	5.50	2	0.01
Fe	587	1	
I			
Mn	41.32	2	2.81
Se	0.24	1	
Zn	25.33	2	3.49
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	4077		
DE	1830		
ME	1699		
NE	878		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Alfalfa Meal
AAFCO #: 3.2, AAFCO 2010, p. 324
IFN #: 1-00-022

Proximate Components, %

	x̄	n	SD
Dry matter	92.30	1	
Crude protein	16.25	2	3.04
Crude fiber			
Ether extract	1.70		
Acid ether extract	1.70	2	0.99
Ash	10.10	2	1.41

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	3.40	1	
Neutral detergent fiber	42.00	2	4.95
Acid detergent fiber	32.15	2	1.91
Hemicellulose	14.70	1	
Acid detergent lignin	8.30	1	
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	16.25	2	3.04	39					
Arg	0.71			64			74		
His	0.37			50			59		
Ile	0.68			59			68		
Leu	1.21			63			71		
Lys	0.74			50			56		
Met	0.25			64			71		
Phe	0.84			62			70		
Thr	0.70			51			63		
Trp	0.24			39			46		
Val	0.86			55			64		
Nonessential									
Ala	0.87			53			59		
Asp	1.93			64			68		
Cys	0.18			20			37		
Glu	1.61			51			58		
Gly	0.81			41			51		
Pro	0.89			61			74		
Ser	0.73			50			59		
Tyr	0.55			59			66		

Minerals

	x̄	n	SD
Macro, %			
Ca	1.14	2	0.56
Cl	0.47		
K	2.30		
Mg	0.23		
Na	0.09		
P	0.30	2	0.06
S	0.29		
Micro, ppm			
Cr			
Cu	10.00		
Fe	333		
I			
Mn	32.00		
Se	0.34		
Zn	24.00		
Phytate P, %			
ATTD of P, %	50		
STTD of P, %	55		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene	94.60		
Vitamin E	49.80		
Water Soluble			
Vitamin B_6	6.50		
Vitamin B_{12}, μg/kg	0		
Biotin	0.54		
Folacin	4.36		
Niacin	38.00		
Pantothenic acid	29.00		
Riboflavin	13.60		
Thiamin	3.40		
Choline	1401		

Energy, kcal/kg

	x̄	n	SD
GE	4038		
DE	1830		
ME	1720		
NE	897		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	2.60		
C-12:0	1.00		
C-14:0	0.95		
C-16:0	12.80		
C-16:1	0.70		
C-18:0	1.90		
C-18:1	2.20		
C-18:2	9.65		
C-18:3	18.50		
C-18:4	0.00		
C-20:0	1.80		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	1.45		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.70		
SFA	20.60		
MUFA	2.90		
PUFA	28.15		
IV	70.73		
IVP	18.39		

TABLE 17-1 Continued

Ingredient: Bakery Meal
AAFCO #: 60.15, AAFCO 2010, p. 375
IFN #: 4-00-466

Proximate Components, %	x̄	n	SD
Dry matter	90.8	1	
Crude protein	12.30	1	
Crude fiber			
Ether extract	8.05		
Acid ether extract			
Ash			
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	52.80		
Neutral detergent fiber	2.00		
Acid detergent fiber	5.51		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	12.30	1							
Arg	0.58	1							
His	0.22	1							
Ile	0.51	1					94		
Leu	0.88	1					90		
Lys	0.41	1					77		
Met	0.19	1					90		
Phe	0.50	1							
Thr	0.42	1					69		
Trp	0.15	1					91		
Val	0.53	1					93		
Nonessential									
Ala	0.52	1							
Asp	0.45	1							
Cys	0.18	1					91		
Glu	1.92	1							
Gly	0.78	1							
Pro	0.98	1							
Ser	0.56	1							
Tyr	0.55	1							

Minerals	x̄	n	SD
Macro, %			
Ca	0.13		
Cl	1.48		
K	0.39		
Mg	0.24		
Na	1.14		
P	0.25		
S	0.02		
Micro, ppm			
Cr			
Cu	5.00		
Fe	28.00		
I			
Mn	65.00		
Se			
Zn	15.00		
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene	4.2		
Vitamin E			
Water Soluble			
Vitamin B_6	4.3		
Vitamin B_{12}, µg/kg	0		
Biotin	0.07		
Folacin	0.20		
Niacin	26		
Pantothenic acid	8.3		
Riboflavin	1.4		
Thiamin	2.9		
Choline	923		
Energy, kcal/kg			
GE	4558		
DE	3940		
ME	3856		
NE	2981		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Barley
AAFCO #: No official definition
IFN #: 4-00-572

Proximate Components, %

	x̄	n	SD
Dry matter	89.90	52	2.65
Crude protein	11.33	76	1.54
Crude fiber	3.90	12	0.70
Ether extract	2.11	33	0.65
Acid ether extract	2.10	4	0.48
Ash	2.38	38	0.42

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	50.21	17	5.20
Neutral detergent fiber	18.29	32	3.38
Acid detergent fiber	5.78	33	1.32
Hemicellulose	14.1	1	
Acid detergent lignin	2.28	9	0.67
Total dietary fiber	15.35	1	
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	11.33	76	1.54	66	20	7.41	79	18	6.03
Arg	0.53	31	0.09	75	22	6.13	85	22	5.92
His	0.27	28	0.07	73	21	7.14	81	21	4.89
Ile	0.37	37	0.07	72	22	5.37	79	22	9.00
Leu	0.72	30	0.11	74	22	4.90	81	22	4.71
Lys	0.40	38	0.05	66	21	8.77	75	21	8.70
Met	0.20	35	0.03	76	19	5.69	82	19	5.62
Phe	0.53	28	0.11	76	21	5.71	81	21	5.31
Thr	0.36	37	0.05	60	22	9.43	76	22	9.56
Trp	0.13	23	0.02	73	8	6.98	82	8	7.03
Val	0.52	37	0.08	71	22	6.88	80	22	7.16
Nonessential									
Ala	0.44	25	0.06	60	21	9.09	73	21	8.36
Asp	0.65	25	0.10	63	21	9.97	75	21	9.78
Cys	0.26	34	0.06	73	17	7.77	81	17	7.54
Glu	2.50	25	0.60	82	21	8.77	87	21	5.64
Gly	0.45	27	0.07	53	21	15.62	82	21	15.75
Pro	1.11	23	0.32	60	16	19.77	88	16	29.25
Ser	0.45	27	0.08	68	21	8.71	80	20	8.38
Tyr	0.28	28	0.06	68	18	14.54	78	17	12.65

Minerals

	x̄	n	SD
Macro, %			
Ca	0.06	32	0.02
Cl	0.12		
K	0.38	3	0.17
Mg	0.14	5	0.01
Na	0.02	1	
P	0.35	39	0.04
S	0.13	3	0.05
Micro, ppm			
Cr			
Cu	5.43	4	1.94
Fe	75.70	2	19.80
I			
Mn	16.29	3	0.77
Se	0.10	1	
Zn	28.09	4	6.95
Phytate P, %	0.22	17	0.04
ATTD of P, %	39	11	5.31
STTD of P, %	45	11	5.84

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene	4.1		
Vitamin E	7.4		
Water Soluble			
Vitamin B_6	5.0		
Vitamin B_{12}, μg/kg	0		
Biotin	0.14		
Folacin	0.31		
Niacin	55		
Pantothenic acid	8.0		
Riboflavin	1.8		
Thiamin	4.5		
Choline	1034		

Energy, kcal/kg

	x̄	n	SD
GE	3939	24	87
DE	3150	8	350
ME	3073		
NE	2327		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	1.60		
C-12:0	0.25		
C-14:0	0.50		
C-16:0	17.88		
C-16:1	0.25		
C-18:0	0.75		
C-18:1	10.50		
C-18:2	43.44		
C-18:3	4.81		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	19.38		
MUFA	10.75		
PUFA	48.25		
IV	101.46		
IVP	16.23		

TABLE 17-1 Continued

Ingredient: Barley, Hulless
AAFCO #: No official definition
IFN #: 4-00-552

Proximate Components, %

	x̄	n	SD
Dry matter	89.58	13	1.80
Crude protein	12.77	20	0.91
Crude fiber	1.1	1	
Ether extract	3.17	9	0.59
Acid ether extract			
Ash	1.94	3	0.39

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	54.56	2	1.73
Neutral detergent fiber	12.55	11	1.84
Acid detergent fiber	2.18	3	0.55
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	12.77	20	0.91	63	9	3.25	69	10	20.64
Arg	0.68	15	0.22	68	10	6.72	77	10	7.79
His	0.40	14	0.14	71	9	7.11	77	9	8.81
Ile	0.35	16	0.12	65	10	7.32	75	10	5.36
Leu	0.74	15	0.16	68	10	5.99	75	10	5.27
Lys	0.51	16	0.14	56	10	5.01	65	10	5.48
Met	0.20	14	0.03	68	8	4.39	73	8	4.21
Phe	0.54	14	0.14	70	9	5.11	75	9	5.21
Thr	0.37	16	0.05	56	10	4.15	70	10	5.13
Trp	0.13	2	0.03						
Val	0.55	14	0.08	66	10	6.95	75	10	6.51
Nonessential									
Ala	0.58	14	0.15	54	10	7.65	66	10	8.81
Asp	0.64	14	0.15	58	10	4.81	70	10	5.57
Cys	0.23	14	0.06	64	8	6.17	72	8	6.06
Glu	3.61	14	1.04	77	10	4.33	80	10	4.56
Gly	0.71	14	0.38	47	10	8.43	77	10	15.25
Pro	0.97	10	0.54	67	6	6.86	112	6	18.91
Ser	0.63	14	0.14	63	10	5.98	73	10	7.42
Tyr	0.25	14	0.12	65	9	8.61	74	9	9.17

Minerals

	x̄	n	SD
Macro, %			
Ca	0.06	5	0.03
Cl	0.10		
K	0.44		
Mg	0.12		
Na	0.02		
P	0.36	9	0.06
S			
Micro, ppm			
Cr			
Cu	5		
Fe	56		
I			
Mn	16		
Se			
Zn	27		
Phytate P, %	0.26	3	0.03
ATTD of P, %	31	1	
STTD of P, %	36	1	

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	6.0		
Water Soluble			
Vitamin B_6	5.6		
Vitamin B_{12}, μg/kg	0		
Biotin	0.07		
Folacin	0.62		
Niacin	48		
Pantothenic acid	6.8		
Riboflavin	1.8		
Thiamin	4.3		
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	3959	5	71
DE	3266		
ME	3179		
NE	2464		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Beans, Faba
AAFCO #: No official definition

Proximate Components, %	x̄	n	SD
Dry matter	88.12	15	0.84
Crude protein	27.16	26	1.83
Crude fiber	8.55	3	0.82
Ether extract	1.30	13	0.14
Acid ether extract			
Ash	3.43	15	0.38
Carbohydrate Components, %			
Lactose	0.00	6	0
Sucrose	0.00	6	0
Raffinose	0.00	6	0
Stachyose	0.00	6	0
Verbascose	0.00	6	0
Oligosaccharides			
Starch	39.22	14	2.38
Neutral detergent fiber	13.29	16	2.39
Acid detergent fiber	10.33	16	1.07
Hemicellulose	1.86	6	0.43
Acid detergent lignin	0.48	8	0.41
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	27.16	26	1.83	73	24	5.88	79	24	5.67
Arg	2.43	19	0.31	88	18	3.28	90	18	3.09
His	0.72	21	0.05	76	20	7.83	79	20	8.10
Ile	1.13	25	0.10	77	25	6.03	81	25	5.25
Leu	1.94	25	0.20	79	25	4.80	82	25	4.94
Lys	1.65	25	0.20	82	25	4.16	85	25	4.26
Met	0.19	25	0.02	65	23	8.22	73	23	11.69
Phe	1.19	21	0.11	77	20	5.37	80	20	5.93
Thr	0.91	25	0.13	70	25	6.37	78	25	6.34
Trp	0.22	16	0.06	61	16	11.40	64	14	11.22
Val	1.22	25	0.13	73	25	5.84	78	25	4.95
Nonessential									
Ala	1.05	19	0.12	72	18	5.45	78	18	5.60
Asp	2.80	19	0.34	81	18	4.39	85	18	4.18
Cys	0.34	23	0.03	56	22	9.80	62	22	10.87
Glu	4.40	19	0.65	85	18	4.10	88	18	3.14
Gly	1.09	19	0.15	62	18	9.85	76	18	9.24
Pro	0.99	13	0.34	50	11	23.39	87	11	20.89
Ser	1.22	19	0.24	77	18	7.47	83	18	5.50
Tyr	0.84	7	0.14	74	10	5.65	82	9	6.80

Minerals	x̄	n	SD
Macro, %			
Ca	0.14	3	0.04
Cl	0.07		
K	1.20		
Mg	0.15		
Na	0.03		
P	0.42	3	0.01
S	0.29		
Micro, ppm			
Cr			
Cu	11		
Fe	75		
I			
Mn	15		
Se	0.02		
Zn	42		
Phytate P, %	0.23	1	
ATTD of P, %	32	1	
STTD of P, %	36	1	

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	0.8		
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, µg/kg	0		
Biotin	0.09		
Folacin			
Niacin	26		
Pantothenic acid	3.0		
Riboflavin	2.9		
Thiamin	5.5		
Choline	1670		

Energy, kcal/kg	x̄	n	SD
GE	4473		
DE	3245		
ME	3060		
NE	2143		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	1.30		
C-12:0	0.00		
C-14:0	0.32		
C-16:0	13.52		
C-16:1	0.00		
C-18:0	2.08		
C-18:1	20.80		
C-18:2	39.68		
C-18:3	2.80		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	15.92		
MUFA	20.80		
PUFA	42.48		
IV	98.16		
IVP	12.76		

TABLE 17-1 Continued

Ingredient: Beans, Phaselous Beans
AAFCO #: No official definition

Proximate Components, %

	x̄	n	SD
Dry matter			
Crude protein	22.90		
Crude fiber			
Ether extract			
Acid ether extract			
Ash			

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	34.40		
Neutral detergent fiber			
Acid detergent fiber			
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility: AID			Digestibility: SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	22.90			49					
Arg	1.91			70			72		
His	0.74						58		
Ile	1.17			50			54		
Leu	2.05			52			55		
Lys	1.67			65			68		
Met	0.29			52			55		
Phe	1.41			41			44		
Thr	1.12			50			55		
Trp	0.27			50			55		
Val	1.33			49			53		
Nonessential									
Ala	1.12			50			55		
Asp	3.06			45			47		
Cys	0.29			38			45		
Glu	4.17			53			56		
Gly	1.06			41			50		
Pro	1.04						60		
Ser	1.54			53			57		
Tyr	0.85			52			56		

Minerals

	x̄	n	SD
Macro, %			
Ca	0.21	1	
Cl			
K			
Mg			
Na			
P	0.52	1	
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %	0.17	1	
ATTD of P, %	38	1	
STTD of P, %	43	1	

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE			
DE			
ME			
NE			

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Blood Cells
AAFCO #: 9.24, AAFCO 2010, p. 328

Proximate Components, %

	x̄	n	SD
Dry matter	93.43	3	2.75
Crude protein	92.83	3	1.27
Crude fiber			
Ether extract	1.50		
Acid ether extract	1.50	1	
Ash	7.00	1	

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	0.00		
Neutral detergent fiber			
Acid detergent fiber	0.00		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	92.83	3	1.27						
Arg	3.37	3	0.19						
His	5.84	2	0.20						
Ile	0.31	3	0.06						
Leu	12.72	3	0.25						
Lys	7.75	3	1.49						
Met	0.97	3	0.32						
Phe	6.66	3	0.40						
Thr	3.43	3	0.78						
Trp	1.72	2	0.09						
Val	8.44	3	0.17						
Nonessential									
Ala									
Asp									
Cys	0.58	2	0.08						
Glu									
Gly									
Pro									
Ser									
Tyr	2.32	2	0.01						

Minerals

	x̄	n	SD
Macro, %			
Ca	0.02	2	0.01
Cl	0.96	2	0.49
K	0.80	1	
Mg	0.02	1	
Na	0.84	2	0.40
P	0.34	2	0.00
S	0.49	1	
Micro, ppm			
Cr			
Cu	2.55	2	0.64
Fe	2675	2	80.04
I			
Mn	0.4	1	
Se	1.00	1	
Zn	15.75	2	0.35
Phytate P, %			
ATTD of P, %	80	1	
STTD of P, %	93	1	

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	5216	1	
DE			
ME			
NE			

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Blood Meal
AAFCO #: 9.61, AAFCO 2010, p. 330
IFN #: 5-26-005

Proximate Components, %				**Amino Acids, %**									
				Total				**Digestibility**					
								AID			**SID**		
	x̄	**n**	**SD**		**x̄**	**n**	**SD**	**x̄**	**n**	**SD**	**x̄**	**n**	**SD**
Dry matter	93.23	7	1.97	Essential									
Crude protein	88.65	13	2.74	CP	88.65	13	2.74	87	3	1.73	89	3	1.84
Crude fiber				Arg	3.83	9	0.43	91	6	5.99	92	5	6.02
Ether extract	1.45	4	0.06	His	5.39	9	0.33	90	6	6.09	91	5	6.09
Acid ether extract	2.00	1		Ile	0.97	9	0.63	68	4	9.25	73	4	9.19
Ash	5.82	5	0.76	Leu	11.45	9	1.10	85	6	1.68	93	5	1.67
Carbohydrate Components, %				Lys	8.60	8	0.57	93	6	1.71	93	5	1.71
				Met	1.18	6	0.20	82	4	1.46	88		
Lactose				Phe	6.15	9	0.82	91	6	1.64	92	5	1.56
Sucrose				Thr	4.36	9	0.32	86	6	2.39	87	5	2.36
Raffinose				Trp	1.34	8	0.35	89	4	3.51	91	3	3.55
Stachyose				Val	7.96	9	0.66	91	6	2.64	92	5	2.62
Verbascose				Nonessential									
Oligosaccharides				Ala	7.29	2	0.75	89	2	1.77	90	2	1.57
Starch	0.00			Asp	7.78	2	2.23	87	2	1.77	88	2	1.64
Neutral detergent fiber				Cys	1.26	4	0.44	81			86		
Acid detergent fiber	0.00			Glu	7.18	2	1.13	86	2	0.40	87	2	0.51
Hemicellulose				Gly	3.69	2	0.24	86			88		
Acid detergent lignin				Pro	5.03	2	1.78	85			88		
Total dietary fiber				Ser	4.64	2	0.21	88	2	1.10	89	2	1.15
Insoluble dietary fiber				Tyr	2.66	5	0.25	82	4	7.56	88		
Soluble dietary fiber													

Minerals				**Vitamins, mg/kg (unless otherwise noted)**				**Fatty Acids, % of Ether Extract**			
	x̄	**n**	**SD**		**x̄**	**n**	**SD**		**x̄**	**n**	**SD**
Macro, %				Fat Soluble				E.E.			
Ca	0.05	2	0.01	β-Carotene				C-12:0			
Cl	0.63	1		Vitamin E	1.0			C-14:0			
K	0.15			Water Soluble				C-16:0			
Mg	0.11			Vitamin B_6	4.4			C-16:1			
Na	0.63	1		Vitamin B_{12}, μg/kg	44			C-18:0			
P	0.21	2	0.15	Biotin	0.03			C-18:1			
S	0.47			Folacin	0.10			C-18:2			
Micro, ppm				Niacin	31			C-18:3			
Cr				Pantothenic acid	2.0			C-18:4			
Cu	7.60	1		Riboflavin	2.4			C-20:0			
Fe	1494	1		Thiamin	0.4			C-20:1			
I				Choline	852			C-20:4			
Mn	0.00	1						C-20:5			
Se								C-22:0			
Zn	49.10	1		**Energy, kcal/kg**				C-22:1			
								C-22:5			
Phytate P, %				GE	5330	1		C-22:6			
ATTD of P, %	67	2	13.29	DE	4376			C-24:0			
STTD of P, %	88	2	2.55	ME	3773			SFA			
				NE	2279			MUFA			
								PUFA			
								IV			
								IVP			

TABLE 17-1 Continued

Ingredient: Blood Plasma
AAFCO #: 9.72, AAFCO 2010, p. 331

Proximate Components, %

	x̄	n	SD
Dry matter	91.97	6	1.1
Crude protein	77.84	12	2.12
Crude fiber			
Ether extract	2.00	2	0
Acid ether extract	2.7	1	
Ash	8.68	4	0.22

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	0.00		
Neutral detergent fiber			
Acid detergent fiber	0.00		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	77.84	12	2.12	76	2	3.96	81	2	7.90
Arg	4.39	13	0.29	88	4	6.11	91	4	6.98
His	2.53	13	0.18	85	4	4.62	87	4	5.30
Ile	2.69	13	0.36	81	4	10.41	85	4	12.32
Leu	7.39	13	0.64	84	4	5.57	87	4	6.89
Lys	6.90	12	0.30	85	4	5.57	87	4	6.31
Met	0.79	13	0.19	80	4	5.74	84	4	9.00
Phe	4.25	13	0.33	83	4	5.55	86	4	7.08
Thr	4.47	13	0.31	77	4	11.32	80	4	12.86
Trp	1.41	10	0.13	85	2	8.56	92	2	12.23
Val	5.12	12	0.27	79	4	9.84	82	4	11.31
Nonessential									
Ala	4.01	7	0.33	81	3	7.89	85	3	7.34
Asp	7.39	7	0.33	83	3	7.62	86	3	6.48
Cys	2.60	9	0.33	82	2	12.23	85	2	7.78
Glu	10.92	7	0.65	85	3	7.72	87	3	6.38
Gly	2.75	7	0.18	73	3	5.96	85	3	2.16
Pro	4.30	7	0.38	87	3	4.42	99	3	5.03
Ser	4.15	7	0.33	84	3	5.49	87	3	5.46
Tyr	3.89	10	0.32	74	3	25.71	76	3	27.25

Minerals

	x̄	n	SD
Macro, %			
Ca	0.13	3	0.04
Cl	1.19	1	
K	0.02	1	
Mg	0.03	1	
Na	2.76	1	
P	1.28	3	0.55
S	1.02	1	
Micro, ppm			
Cr			
Cu	14.75	2	4.60
Fe	81	2	5.59
I			
Mn	2.50	1	
Se	1.60	1	
Zn	13.45	2	0.64
Phytate P, %			
ATTD of P, %	92	1	
STTD of P, %	98	1	

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	4733	3	98
DE	4546	1	
ME	4017		
NE	2506		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Brewers Grains
AAFCO #: 15.1, AAFCO 2010, p. 333
IFN #: 5-00-516

Proximate Components, %	x̄	n	SD	Amino Acids, % Total	x̄	n	SD	AID x̄	AID n	AID SD	SID x̄	SID n	SID SD
Dry matter	92.00			Essential									
Crude protein	26.50			CP	26.50			70					
Crude fiber				Arg	1.53			81			93		
Ether extract	4.72			His	0.53			70			83		
Acid ether extract	7.30			Ile	1.02			81			87		
Ash				Leu	2.08			73			86		
Carbohydrate Components, %				Lys	1.08			69			80		
				Met	0.45			74			87		
Lactose				Phe	1.22			81			90		
Sucrose				Thr	0.95			70			80		
Raffinose				Trp	0.26			73			81		
Stachyose				Val	1.26			73			84		
Verbascose				Nonessential									
Oligosaccharides				Ala	1.43			71			74		
Starch	5.30			Asp	1.94			70			74		
Neutral detergent fiber	48.70			Cys	0.49			67			76		
Acid detergent fiber	20.14			Glu	5.13			71			74		
Hemicellulose				Gly	1.10			66			74		
Acid detergent lignin				Pro	2.36			69			74		
Total dietary fiber				Ser	1.20			68			74		
Insoluble dietary fiber				Tyr	0.88			91			93		
Soluble dietary fiber													

Minerals	x̄	n	SD	Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD	Fatty Acids, % of Ether Extract	x̄	n	SD
Macro, %				Fat Soluble				E.E.	6.70		
Ca	0.21			β-Carotene	0.2			C-12:0	0.00		
Cl	0.15			Vitamin E				C-14:0	0.54		
K	0.08			Water Soluble				C-16:0	9.99		
Mg	0.16			Vitamin B_6	0.7			C-16:1	0.00		
Na	0.26			Vitamin B_{12}, μg/kg	0			C-18:0	0.68		
P	0.58			Biotin	0.06			C-18:1	5.40		
S	0.31			Folacin	7.10			C-18:2	24.93		
Micro, ppm				Niacin	43			C-18:3	2.52		
Cr				Pantothenic acid	8.0			C-18:4	0.00		
Cu	21			Riboflavin	1.4			C-20:0	0.00		
Fe	250			Thiamin	0.6			C-20:1	0.00		
I				Choline	1723			C-20:4	0.00		
Mn	38							C-20:5	0.00		
Se	0.70							C-22:0	0.00		
Zn	62			**Energy, kcal/kg**				C-22:1	0.00		
								C-22:5	0.00		
Phytate P, %	0.35			GE	4805			C-22:6	0.00		
ATTD of P, %	32			DE	2100			C-24:0	0.00		
STTD of P, %	39			ME	1920			SFA	11.21		
				NE	1155			MUFA	5.40		
								PUFA	27.45		
								IV	56.86		
								IVP	38.10		

TABLE 17-1 Continued

Ingredient: Camelina Meal
AAFCO #: No official definition

Proximate Components, %	x̄	n	SD
Dry matter			
Crude protein	35.15	2	2.90
Crude fiber	11.9	1	
Ether extract	18.5	1	
Acid ether extract			
Ash			
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	6.50		
Neutral detergent fiber			
Acid detergent fiber			
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total x̄	Total n	Total SD	AID x̄	AID n	AID SD	SID x̄	SID n	SID SD
Essential									
CP	35.15	2	2.90						
Arg	2.11	2	0.96						
His	0.80	2	0.06						
Ile	1.32	2	0.09						
Leu	2.21	2	0.12						
Lys	1.62	2	0.16						
Met	0.87	2	0.06						
Phe	1.40	2	0.09						
Thr	1.30	2	0.10						
Trp	0.42	2	0.11						
Val	1.81	2	0.14						
Nonessential									
Ala	1.55	2	0.08						
Asp	2.75	2	0.16						
Cys	0.95	1							
Glu	5.77	2	0.05						
Gly	1.75	2	0.09						
Pro									
Ser	1.34	2	0.07						
Tyr	0.77	2	0.06						

Minerals	x̄	n	SD
Macro, %			
Ca	0.21	2	0.00
Cl			
K	1.23	2	0.11
Mg	0.40	2	0.02
Na	0.01	2	0.00
P	0.77	2	0.03
S	0.72	2	0.12
Micro, ppm			
Cr			
Cu	6.80	2	0.35
Fe	137	2	16.26
I			
Mn	23.85	2	1.91
Se			
Zn	47.95	2	4.17
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			
Energy, kcal/kg			
GE	4931	1	
DE			
ME			
NE			

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Canola, Full Fat
AAFCO #: No official definition

Proximate Components, %	x̄	n	SD
Dry matter	94.57	5	1.56
Crude protein	22.06	6	4.67
Crude fiber	6.10	2	0.13
Ether extract	43.61	5	3.51
Acid ether extract			
Ash	3.71	2	0.06
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	0.70		
Neutral detergent fiber	16.71	5	3.07
Acid detergent fiber	12.57	5	0.94
Hemicellulose	1.46	2	0.60
Acid detergent lignin	5.40	2	0.33
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	22.06	6	4.67	66			64	1	
Arg	1.00	3	0.06	81			84		
His	0.60	3	0.06	77			80		
Ile	0.60	3	0.12	73			74		
Leu	1.14	3	0.06	73			76		
Lys	1.01	3	0.05	70			73		
Met	0.38	3	0.04	78			81		
Phe	0.73	3	0.10	73			77		
Thr	0.83	3	0.07	64			70		
Trp	0.23	2	0.01	66			71		
Val	0.83	3	0.17	66			71		
Nonessential									
Ala	0.84	1		70			73	1	
Asp	1.48	1		66			71		
Cys	0.46	3	0.02	66			70		
Glu	3.66	1		77	1		84		
Gly	0.74	1		62	1		73		
Pro	0.60			70			79		
Ser	0.85	1		69			76		
Tyr	0.55	1		70			75		

Minerals	x̄	n	SD
Macro, %			
Ca	0.36	3	0.05
Cl			
K	1.02	1	
Mg	0.19	1	
Na			
P	0.70	3	0.14
S			
Micro, ppm			
Cr			
Cu	2.50	1	
Fe	51.60	1	
I			
Mn	38.10	1	
Se			
Zn	27.23	1	
Phytate P, %	0.79	1	
ATTD of P, %	28		
STTD of P, %	32		

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			
Energy, kcal/kg			
GE	6371	1	
DE	5234		
ME	5084		
NE	4059		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	42.00		
C-12:0	0.00		
C-14:0	0.10		
C-16:0	3.99		
C-16:1	0.38		
C-18:0	1.71		
C-18:1	55.10		
C-18:2	19.48		
C-18:3	9.31		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	5.80		
MUFA	55.48		
PUFA	28.79		
IV	110.59		
IVP	464.49		

TABLE 17-1 Continued

Ingredient: Canola Meal, Expelled
AAFCO #: 71.25, AAFCO 2010, p. 385
IFN #: 5-03-870

Proximate Components, %	x̄	n	SD
Dry matter	93.11	3	2.21
Crude protein	35.19	14	4.08
Crude fiber	9.77	3	2.66
Ether extract	9.97	4	3.34
Acid ether extract			
Ash	6.39	3	0.19
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	3.80		
Neutral detergent fiber	23.77	4	2.22
Acid detergent fiber	17.57	3	0.72
Hemicellulose	5.48	1	
Acid detergent lignin	7.31	1	
Total dietary fiber	25.81	1	
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	35.19	14	4.08	70	6	5.05	75	6	4.26
Arg	1.76	12	0.26	80	13	6.37	83	13	6.79
His	0.82	12	0.25	76	13	11.46	78	13	11.30
Ile	1.67	12	0.54	76	13	8.17	78	13	7.94
Leu	1.95	12	0.30	77	13	7.39	78	13	7.60
Lys	1.58	12	0.58	70	13	13.25	71	13	13.18
Met	0.61	12	0.16	82	13	4.23	83	13	4.30
Phe	1.48	12	0.49	79	12	8.37	80	12	8.51
Thr	1.22	12	0.20	67	13	11.84	70	13	12.09
Trp	0.32	4	0.21	72	4	13.09	73		
Val	1.63	12	0.36	71	13	11.00	73	13	10.74
Nonessential									
Ala	1.36	9	0.11	73	12	8.45	76	12	8.66
Asp	2.17	9	0.33	71	12	10.61	73	12	10.76
Cys	0.79	11	0.29	74	10	8.38	76	10	8.19
Glu	5.82	9	0.97	82	12	6.78	84	12	7.24
Gly	1.67	9	0.24	64	12	14.96	70	12	17.39
Pro	0.99	4	0.85	66	7	9.87	132	7	71.15
Ser	0.99	9	0.27	68	12	14.53	71	12	15.55
Tyr	0.78	10	0.16	72	12	11.11	74	12	11.65

Minerals	x̄	n	SD
Macro, %			
Ca	0.69	9	0.11
Cl			
K			
Mg	0.52	1	
Na			
P	1.15	10	0.16
S			
Micro, ppm			
Cr			
Cu	5.40	1	
Fe	232	1	
I			
Mn	60.30	1	
Se			
Zn	72.00	1	
Phytate P, %	0.87	2	0.06
ATTD of P, %	28		
STTD of P, %	32		

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			
Energy, kcal/kg			
GE	4873	3	120
DE	3779	2	17
ME	3540		
NE	2351		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	2.30		
C-12:0	0.00		
C-14:0	0.08		
C-16:0	3.36		
C-16:1	0.32		
C-18:0	1.44		
C-18:1	46.40		
C-18:2	16.40		
C-18:3	7.84		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	4.88		
MUFA	46.72		
PUFA	24.24		
IV	93.13		
IVP	21.42		

TABLE 17-1 Continued

Ingredient: Canola Meal, Solvent Extracted
AAFCO #: 71.77, AAFCO 2010, p. 384
IFN #: 5-05-146

Proximate Components, %

	x̄	n	SD
Dry matter	91.33	46	2.40
Crude protein	37.50	96	3.01
Crude fiber	10.50	16	1.59
Ether extract	3.22	34	1.23
Acid ether extract			
Ash	6.89	22	0.84

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides	26.77	1	
Starch	6.07	2	1.37
Neutral detergent fiber	22.64	33	4.51
Acid detergent fiber	15.42	24	3.18
Hemicellulose	5.29	1	
Acid detergent lignin	3.36	7	2.49
Total dietary fiber	26.6	3	1.63
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	37.50	96	3.01	68	42	9.49	74	39	8.24
Arg	2.28	78	0.57	82	44	6.42	85	41	5.56
His	1.07	71	0.25	75	39	10.89	78	36	10.24
Ile	1.42	78	0.14	72	44	9.22	76	41	8.34
Leu	2.45	78	0.27	74	44	7.88	78	41	6.44
Lys	2.07	78	0.33	71	44	10.43	74	41	9.65
Met	0.71	55	0.18	82	41	7.77	85	39	4.06
Phe	1.48	72	0.24	74	39	8.60	77	36	8.42
Thr	1.55	78	0.38	65	44	9.67	70	41	9.64
Trp	0.43	35	0.10	66	22	9.49	71		
Val	1.78	78	0.21	69	44	10.95	74	41	9.78
Nonessential									
Ala	1.61	50	0.22	72	29	7.99	77	27	7.25
Asp	2.56	48	0.22	72	29	7.73	76	27	7.11
Cys	0.86	49	0.12	70	33	8.46	74	31	7.44
Glu	6.35	48	0.94	81	29	7.37	84	27	3.94
Gly	1.80	50	0.25	69	29	8.71	78	27	8.60
Pro	2.02	48	0.78	66	27	13.91	92	25	11.82
Ser	1.49	50	0.24	69	29	8.50	75	27	6.51
Tyr	1.06	48	0.22	72	27	9.75	77	22	8.33

Minerals

	x̄	n	SD
Macro, %			
Ca	0.69	19	0.10
Cl	0.11		
K	1.69	1	
Mg	0.28	1	
Na	0.07		
P	1.08	19	0.07
S	0.85		
Micro, ppm			
Cr			
Cu	4.90	1	
Fe	163	1	
I			
Mn	76.90	1	
Se	1.10		
Zn	49.73	1	
Phytate P, %	0.65	5	0.30
ATTD of P, %	28	7	4.02
STTD of P, %	32	7	5.73

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	13.4		
Water Soluble			
Vitamin B_6	7.2		
Vitamin B_{12}, μg/kg	0		
Biotin	0.98		
Folacin	0.83		
Niacin	160		
Pantothenic acid	9.5		
Riboflavin	5.8		
Thiamin	5.2		
Choline	6700		

Energy, kcal/kg

	x̄	n	SD
GE	4332	19	112
DE	3273	20	361
ME	3013		
NE	1890		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	2.30		
C-12:0	0.00		
C-14:0	0.08		
C-16:0	3.36		
C-16:1	0.32		
C-18:0	1.44		
C-18:1	46.40		
C-18:2	16.40		
C-18:3	7.84		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	4.88		
MUFA	46.72		
PUFA	24.24		
IV	93.13		
IVP	21.42		

TABLE 17-1 Continued

Ingredient: Cassava Meal
AAFCO #: No official definition
IFN #: 4-01-152

Proximate Components, %

	$\bar{x}$	n	SD
Dry matter	88.09	7	1.03
Crude protein	2.88	7	0.75
Crude fiber	4.18	6	1.08
Ether extract	0.94	7	0.20
Acid ether extract			
Ash	5.70	7	0.75

Carbohydrate Components, %

	$\bar{x}$	n	SD
Lactose	0.00	5	0.00
Sucrose	0.00	5	0.00
Raffinose	0.00	5	0.00
Stachyose	0.00	5	0.00
Verbascose	0.00	5	0.00
Oligosaccharides			
Starch	67.85	4	4.90
Neutral detergent fiber	6.55	3	1.21
Acid detergent fiber	5.99	5	1.95
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	$\bar{x}$	n	SD	$\bar{x}$	n	SD	$\bar{x}$	n	SD
Essential									
CP	2.88	7	0.75						
Arg	0.18						90		
His	0.08						80		
Ile	0.11						81		
Leu	0.19						79		
Lys	0.12						71		
Met	0.04						84		
Phe	0.15						80		
Thr	0.11						73		
Trp	0.04						77		
Val	0.14						76		
Nonessential									
Ala									
Asp									
Cys	0.05						68		
Glu									
Gly									
Pro									
Ser									
Tyr	0.04						76		

Minerals

	$\bar{x}$	n	SD
Macro, %			
Ca	0.28	1	
Cl	0.07		
K	0.49		
Mg	0.11		
Na	0.03		
P	0.12	2	0.03
S	0.50		
Micro, ppm			
Cr			
Cu	4		
Fe	18		
I			
Mn	28		
Se	0.10		
Zn	10		
Phytate P, %	0.04	1	
ATTD of P, %	10	1	
STTD of P, %	24	1	

Vitamins, mg/kg (unless otherwise noted)

	$\bar{x}$	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	0.2		
Water Soluble			
Vitamin B_6	0.7		
Vitamin B_{12}, μg/kg	0		
Biotin	0.05		
Folacin			
Niacin	3		
Pantothenic acid	0.3		
Riboflavin	0.8		
Thiamin	1.6		
Choline			

Energy, kcal/kg

	$\bar{x}$	n	SD
GE	3451	5	83
DE	3407	1	
ME	3387		
NE	2647		

Fatty Acids, % of Ether Extract

	$\bar{x}$	n	SD
E.E.	0.70		
C-12:0	3.12		
C-14:0	1.36		
C-16:0	25.52		
C-16:1	0.56		
C-18:0	2.32		
C-18:1	28.16		
C-18:2	13.12		
C-18:3	6.08		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	32.80		
MUFA	28.72		
PUFA	19.20		
IV	66.23		
IVP	4.64		

TABLE 17-1 Continued

Ingredient: Citrus Pulp
AAFCO #: 21.1, AAFCO 2010, p. 337
IFN #: 4-01-237

Proximate Components, %	x̄	n	SD
Dry matter	90.9	2	1.7
Crude protein	6.64	3	1.29
Crude fiber			
Ether extract	2.49	3	0.42
Acid ether extract			
Ash	7.73	1	

Carbohydrate Components, %	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	2.53	2	0.66
Neutral detergent fiber	21.23	2	2.11
Acid detergent fiber	20.2	2	3.57
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	6.64	3	1.29						
Arg	0.26						89		
His	0.12						84		
Ile	0.18						81		
Leu	0.32						83		
Lys	0.19						77		
Met	0.07						85		
Phe	0.24						84		
Thr	0.18						76		
Trp	0.05						77		
Val	0.24						78		
Nonessential									
Ala	0.25								
Asp	0.60								
Cys	0.08						73		
Glu	0.52								
Gly	0.24								
Pro	0.53								
Ser	0.23								
Tyr	0.16						86		

Minerals	x̄	n	SD
Macro, %			
Ca	1.71	3	0.41
Cl			
K	0.74	1	
Mg	0.11	1	
Na	0.52	1	
P	0.09	3	0.01
S	0.07	1	
Micro, ppm			
Cr			
Cu	2.69	1	
Fe	76.87	1	
I			
Mn	8.52	1	
Se			
Zn	30.59	1	
Phytate P, %	0.04	1	
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg	x̄	n	SD
GE	3828	1	
DE	2773		
ME	2728		
NE	1757		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	2.20		
C-12:0	0.48		
C-14:0	0.42		
C-16:0	15.54		
C-16:1	0.00		
C-18:0	2.88		
C-18:1	15.54		
C-18:2	21.54		
C-18:3	3.84		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	19.32		
MUFA	15.54		
PUFA	25.38		
IV	63.45		
IVP	13.96		

TABLE 17-1 Continued

Ingredient: Copra Expelled
AAFCO #: No official definition

Proximate Components, %	x̄	n	SD	Amino Acids, % Total	x̄	n	SD	AID x̄	AID n	AID SD	SID x̄	SID n	SID SD
Dry matter				Essential									
Crude protein	20.40			CP	20.40			52					
Crude fiber				Arg	2.45			56			58		
Ether extract				His	0.40			53			58		
Acid ether extract				Ile	0.72			53			58		
Ash				Leu	1.39			54			58		
Carbohydrate Components, %				Lys	0.56			51			58		
				Met	0.34			55			58		
Lactose				Phe	0.94			54			58		
Sucrose				Thr	0.67			49			58		
Raffinose				Trp	0.16			49			58		
Stachyose				Val	1.08			53			58		
Verbascose				Nonessential									
Oligosaccharides				Ala	0.94			53			58		
Starch	0.60			Asp	1.77			53			58		
Neutral detergent fiber				Cys	0.34			52			58		
Acid detergent fiber				Glu	4.08			55			58		
Hemicellulose				Gly	0.94			48			58		
Acid detergent lignin				Pro	0.79			43			58		
Total dietary fiber				Ser	0.94			51			58		
Insoluble dietary fiber				Tyr	0.54			52			58		
Soluble dietary fiber													

Minerals	x̄	n	SD	Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD	Fatty Acids, % of Ether Extract	x̄	n	SD
Macro, %				Fat Soluble				E.E.	8.20		
Ca	0.04	1		β-Carotene				C-12:0	41.76		
Cl				Vitamin E				C-14:0	15.93		
K				Water Soluble				C-16:0	8.01		
Mg				Vitamin B_6				C-16:1	0.36		
Na				Vitamin B_{12},μg/kg				C-18:0	2.70		
P	0.52	1		Biotin				C-18:1	5.85		
S				Folacin				C-18:2	1.62		
Micro, ppm				Niacin				C-18:3	0.09		
Cr				Pantothenic acid				C-18:4	0.00		
Cu				Riboflavin				C-20:0	0.45		
Fe				Thiamin				C-20:1	0.00		
I				Choline				C-20:4	0.00		
Mn								C-20:5	0.00		
Se								C-22:0	0.00		
Zn				**Energy, kcal/kg**				C-22:1	0.00		
								C-22:5	0.00		
Phytate P, %	0.22	1		GE	4308	1		C-22:6	0.00		
ATTD of P, %	61	1		DE	3756	1		C-24:0	0.00		
STTD of P, %	72	1		ME	3617			SFA	80.64		
				NE				MUFA	6.21		
								PUFA	1.71		
								IV	8.79		
								IVP	7.21		

TABLE 17-1 Continued

Ingredient: Copra Meal
AAFCO #: 71.61, AAFCO 2010, p. 384
IFN #: 5-01-573

Proximate Components, %

	$\bar{x}$	n	SD
Dry matter	92.00		
Crude protein	21.90		
Crude fiber			
Ether extract	3.00		
Acid ether extract			
Ash			

Carbohydrate Components, %

	$\bar{x}$	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	2.60		
Neutral detergent fiber	51.30		
Acid detergent fiber	25.50		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	$\bar{x}$	n	SD	$\bar{x}$	n	SD	$\bar{x}$	n	SD
Essential									
CP	21.90			52					
Arg	2.38			81			88		
His	0.39			63			70		
Ile	0.75			64			72		
Leu	1.36			68			73		
Lys	0.58			51			64		
Met	0.35			67			77		
Phe	0.84			71			75		
Thr	0.67			51			67		
Trp	0.19			63			69		
Val	1.07			68			71		
Nonessential									
Ala	0.83			53			58		
Asp	1.58			54			58		
Cys	0.29			54			65		
Glu	3.71			55			58		
Gly	0.83			49			58		
Pro	0.69			44			58		
Ser	0.85			51			58		
Tyr	0.58			53			72		

Minerals

	$\bar{x}$	n	SD
Macro, %			
Ca	0.13	1	
Cl	0.37		
K	1.83		
Mg	0.31		
Na	0.04		
P	0.58	1	
S	0.31		
Micro, ppm			
Cr			
Cu	25		
Fe	486		
I			
Mn	69		
Se			
Zn	49		
Phytate P, %	0.26	1	
ATTD of P, %	34	1	
STTD of P, %	44	1	

Vitamins, mg/kg (unless otherwise noted)

	$\bar{x}$	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	7.7		
Water Soluble			
Vitamin B_6	4.4		
Vitamin B_{12}, μg/kg			
Biotin	0.25		
Folacin	0.30		
Niacin	28		
Pantothenic acid	6.5		
Riboflavin	3.5		
Thiamin	0.70		
Choline	1089		

Energy, kcal/kg

	$\bar{x}$	n	SD
GE	4199		
DE	3010		
ME	2861		
NE	1747		

Fatty Acids, % of Ether Extract

	$\bar{x}$	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Corn, Yellow Dent
AAFCO #: 48.4, AAFCO 2010, p. 355
IFN #: 4-02-861

Proximate Components, %

	x̄	n	SD
Dry matter	88.31	133	2.41
Crude protein	8.24	163	0.93
Crude fiber	1.98	78	0.61
Ether extract	3.48	115	0.78
Acid ether extract	3.68	7	1.26
Ash	1.30	76	0.32

Carbohydrate Components, %

	x̄	n	SD
Lactose	0.00	8	0.00
Sucrose	0.09	9	0.28
Raffinose	0.01	9	0.04
Stachyose	0.01	9	0.02
Verbascose	0.01	9	0.02
Oligosaccharides			
Starch	62.55	37	4.61
Neutral detergent fiber	9.11	54	1.97
Acid detergent fiber	2.88	45	0.83
Hemicellulose			
Acid detergent lignin	0.32	2	0.12
Total dietary fiber	13.73	2	4.65
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	8.24	163	0.93	65	19	10.34	80	19	9.18
Arg	0.37	127	0.05	75	27	7.98	87	27	7.62
His	0.24	121	0.05	77	27	5.75	83	27	5.42
Ile	0.28	128	0.06	73	27	6.70	82	27	6.26
Leu	0.96	121	0.15	82	27	7.47	87	27	7.37
Lys	0.25	132	0.04	60	27	11.63	74	27	10.62
Met	0.18	130	0.03	77	25	11.15	83	25	10.12
Phe	0.39	120	0.05	78	27	6.89	85	27	6.58
Thr	0.28	129	0.04	61	27	10.29	77	27	10.70
Trp	0.06	111	0.01	62	13	10.01	80	13	9.54
Val	0.38	128	0.05	71	27	8.23	82	27	7.38
Nonessential									
Ala	0.60	87	0.08	77	22	5.78	81	21	16.94
Asp	0.54	87	0.09	71	22	9.21	79	21	16.81
Cys	0.19	112	0.02	75	19	6.37	80	20	17.60
Glu	1.48	79	0.26	80	22	11.31	84	21	18.99
Gly	0.31	85	0.04	50	22	24.33	84	21	22.06
Pro	0.71	83	0.12	50	18	24.62	93	17	18.98
Ser	0.38	81	0.06	74	22	7.18	82	21	17.20
Tyr	0.26	101	0.07	74	22	7.17	79	20	17.83

Minerals

	x̄	n	SD
Macro, %			
Ca	0.02	61	0.01
Cl	0.05		
K	0.32	6	0.01
Mg	0.12	9	0.07
Na	0.02	2	0.00
P	0.26	76	0.05
S			
Micro, ppm			
Cr			
Cu	3.41	5	2.02
Fe	18.38	3	10.86
I			
Mn	4.31	5	2.50
Se	0.07		
Zn	16.51	5	4.96
Phytate P, %	0.21	10	0.04
ATTD of P, %	26	17	7.11
STTD of P, %	34	17	7.22

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene	0.8		
Vitamin E	11.65	1	
Water Soluble			
Vitamin B_6	5.0		
Vitamin B_{12}, μg/kg	0		
Biotin	0.06		
Folacin	0.15		
Niacin	24		
Pantothenic acid	6.0		
Riboflavin	1.2		
Thiamin	3.5		
Choline	620		

Energy, kcal/kg

	x̄	n	SD
GE	3933	48	86
DE	3451	11	111
ME	3395		
NE	2672		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	4.74		
C-12:0	0.00		
C-14:0	0.00		
C-16:0	12.00		
C-16:1	0.08		
C-18:0	1.58		
C-18:1	26.31		
C-18:2	44.24		
C-18:3	1.37		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:5			
C-22:6			
C-22:6			
C-24:0			
SFA	13.59		
MUFA	26.39		
PUFA	45.61		
IV	107.54		
IVP	50.98		

TABLE 17-1 Continued

Ingredient: Corn, Nutridense
AAFCO #: 48.4, AAFCO 2010, p. 355
IFN #: 4-02-861

Proximate Components, %	x̄	n	SD
Dry matter	87.93	8	2.55
Crude protein	9.02	12	1.12
Crude fiber	2.22	2	0.06
Ether extract	4.85	6	1.08
Acid ether extract	5.01	3	0.48
Ash	1.44	8	0.26
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	67.44	4	3.07
Neutral detergent fiber	6.98	2	0.96
Acid detergent fiber	2.33	1	
Hemicellulose			
Acid detergent lignin			
Total dietary fiber	9.6	2	0.33
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total x̄	Total n	Total SD	AID x̄	AID n	AID SD	SID x̄	SID n	SID SD
Essential									
CP	9.02	12	1.12	74	1		83	1	
Arg	0.44	9	0.05	75	3	4.61	83	3	4.56
His	0.26	9	0.03	77	3	4.80	82	3	3.93
Ile	0.32	10	0.04	76	3	2.43	85	3	3.04
Leu	1.09	10	0.15	83	3	2.50	87	3	2.52
Lys	0.27	10	0.05	65	3	6.20	79	3	5.06
Met	0.20	10	0.01	79	3	5.57	83	3	4.10
Phe	0.43	7	0.05	80	3	3.26	86	3	4.12
Thr	0.31	10	0.03	62	3	9.61	78	3	8.03
Trp	0.07	4	0.01	65	1		76	1	
Val	0.44	10	0.05	72	3	5.75	81	3	5.04
Nonessential									
Ala	0.66	7	0.08	76	3	6.38	85	1	
Asp	0.60	7	0.08	75	3	2.00	82	1	
Cys	0.22	8	0.02	78	1		82	1	
Glu	1.66	7	0.21	68	3	18.83	75	1	
Gly	0.32	5	0.01	51	3	29.65	88	1	
Pro	0.77	7	0.09	45	3	3.82	85	1	
Ser	0.42	7	0.05	74	3	3.91	85	1	
Tyr	0.28	7	0.04	70	3	7.98	80	1	

Minerals	x̄	n	SD
Macro, %			
Ca	0.04	3	0.02
Cl			
K	0.30	2	0.03
Mg	0.11	2	0.01
Na			
P	0.27	7	0.02
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %	0.16	2	0.11
ATTD of P, %	26		
STTD of P, %	34		

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg	x̄	n	SD
GE	3987	6	140
DE	3455	1	
ME	3394		
NE	2718		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Corn Bran
AAFCO #: 48.2, AAFCO 2010, p. 355
IFN #: 4-02-841

Proximate Components, %

	x̄	n	SD
Dry matter	88.50	2	1.41
Crude protein	9.53	2	0.19
Crude fiber	6.61	2	0.35
Ether extract	8.52	2	1.36
Acid ether extract			
Ash	2.53	2	0.03

Carbohydrate Components, %

	x̄	n	SD
Lactose	0.00	2	0.00
Sucrose	0.00	2	0.00
Raffinose	0.00	2	0.00
Stachyose	0.00	2	0.00
Verbascose	0.00	2	0.00
Oligosaccharides			
Starch	31.73	1	
Neutral detergent fiber	32.96	1	
Acid detergent fiber	9.23	1	
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total x̄	Total n	Total SD	AID x̄	AID n	AID SD	SID x̄	SID n	SID SD
Essential									
CP	9.53	2	0.19	63					
Arg	0.56						89		
His	0.29						83		
Ile	0.30			70			81		
Leu	0.97			80			84		
Lys	0.35			59			74		
Met	0.19			82			86		
Phe	0.37			74			83		
Thr	0.35			55			74		
Trp	0.08			54			75		
Val	0.46			69			79		
Nonessential									
Ala	0.67			74			80		
Asp	0.65			62			73		
Cys	0.20			64			73		
Glu	1.49			73			80		
Gly	0.41			50			70		
Pro	0.76			65			77		
Ser	0.43			68			81		
Tyr	0.30			76			85		

Minerals

	x̄	n	SD
Macro, %			
Ca	0.47		
Cl			
K			
Mg			
Na			
P	0.29		
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %	20		
STTD of P, %	27		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	4652		
DE	2649	3	55
ME	2584		
NE	1977		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	0.92		
C-12:0	0.00		
C-14:0	0.00		
C-16:0	12.07		
C-16:1	0.11		
C-18:0	1.63		
C-18:1	26.41		
C-18:2	44.35		
C-18:3	1.41		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	13.70		
MUFA	26.52		
PUFA	45.76		
IV	107.97		
IVP	9.93		

TABLE 17-1 Continued

Ingredient: Corn DDG
AAFCO #: 27.5, AAFCO 2010, p. 343
IFN #: 5-02-842

Proximate Components, %

	x̄	n	SD
Dry matter	90.82	2	3.98
Crude protein	28.89	3	2.56
Crude fiber	9.48	1	
Ether extract	8.69	2	1.09
Acid ether extract			
Ash	3.04	2	1.67
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	3.83	1	
Neutral detergent fiber	41.86	3	6.71
Acid detergent fiber	15.55	3	4.33
Hemicellulose			
Acid detergent lignin			
Total dietary fiber	43.90	1	
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	28.89	3	2.56	67	1		76	1	
Arg	1.22	2	0.10	75	1		83	1	
His	0.78	2	0.14	81	1		84	1	
Ile	1.19	2	0.15	80	1		83	1	
Leu	4.03	2	0.47	84	1		86	1	
Lys	0.87	2	0.08	73	1		78	1	
Met	0.62	2	0.08	88	1		89	1	
Phe	1.62	2	0.14	83	1		87	1	
Thr	1.13	2	0.04	71	1		78	1	
Trp	0.21	2	0.01	63	1		71		
Val	1.56	2	0.23	78	1		81	1	
Nonessential									
Ala	2.33	2	0.24	78	1		82	1	
Asp	1.94	2	0.11	69	1		74	1	
Cys	0.57	2	0.04	77	1		81	1	
Glu	5.14	2	0.11	85	1		87	1	
Gly	1.09	2	0.12	40	1		66	1	
Pro	2.54	2	0.05	12	1		55	1	
Ser	1.39	2	0.09	76	1		82	1	
Tyr	1.31	1					80		

Minerals

	x̄	n	SD
Macro, %			
Ca	0.08	2	0.09
Cl	0.08		
K	0.17		
Mg	0.25		
Na	0.09		
P	0.56	2	0.11
S			
Micro, ppm			
Cr			
Cu	45		
Fe	220		
I			
Mn	22		
Se	0.40		
Zn	55		
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene	3.0		
Vitamin E	12.9		
Water Soluble			
Vitamin B_6	4.4		
Vitamin B_{12}, μg/kg	0		
Biotin	0.49		
Folacin	0.90		
Niacin	37		
Pantothenic acid	11.7		
Riboflavin	5.2		
Thiamin	1.7		
Choline	1180		

Energy, kcal/kg

	x̄	n	SD
GE	4919	5	342
DE	3355	4	173
ME	3158		
NE	2109		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Corn DDGS, > 10% Oil
AAFCO #: 27.6, AAFCO 2010, p. 343
IFN #: 5-02-843

Proximate Components, %

	x̄	n	SD
Dry matter	89.31	59	1.91
Crude protein	27.33	81	1.53
Crude fiber	7.06	12	1.24
Ether extract	10.43	34	1.03
Acid ether extract	11.27	8	1.36
Ash	4.11	39	0.91

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	6.73	32	1.70
Neutral detergent fiber	32.50	76	5.42
Acid detergent fiber	11.75		
Hemicellulose			
Acid detergent lignin	2.61	1	
Total dietary fiber	31.35	8	3.28
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	27.33	81	1.53	64	40	5.19	74	35	5.83
Arg	1.16	67	0.17	74	40	5.02	81	40	5.25
His	0.71	67	0.07	74	40	4.97	78	40	4.75
Ile	1.02	77	0.09	72	40	5.03	76	40	4.87
Leu	3.13	67	0.46	82	40	4.09	84	40	4.00
Lys	0.77	68	0.12	55	40	10.76	61	40	8.75
Met	0.55	68	0.09	80	40	4.30	82	40	4.13
Phe	1.34	67	0.10	78	40	3.87	81	40	3.96
Thr	0.99	64	0.08	64	40	6.51	71	40	5.73
Trp	0.21	67	0.03	63	40	8.34	71	40	8.16
Val	1.35	67	0.12	71	40	5.16	75	40	4.95
Nonessential									
Ala	1.93	58	0.16	74	40	4.72	79	40	4.64
Asp	1.82	58	0.18	63	40	5.73	69	40	5.52
Cys	0.51	60	0.11	69	40	5.97	73	40	5.70
Glu	4.35	58	0.69	76	40	7.81	81	40	5.63
Gly	1.04	56	0.09	42	40	10.79	64	40	11.16
Pro	2.09	58	0.18	34	40	19.40	74	40	21.54
Ser	1.18	58	0.16	70	40	5.36	77	40	5.48
Tyr	1.04	38	0.14	78	20	4.48	81	20	3.98

Minerals

	x̄	n	SD
Macro, %			
Ca	0.12	38	0.19
Cl			
K	0.90	22	0.12
Mg	0.29	25	0.04
Na	0.22	23	0.13
P	0.73	66	0.10
S	0.66	19	0.28
Micro, ppm			
Cr			
Cu	7.65	22	4.14
Fe	126	21	73.07
I			
Mn	17.92	22	10.05
Se			
Zn	65.05	21	19.62
Phytate P, %	0.26	1	
ATTD of P, %	60	17	6.49
STTD of P, %	65	17	6.54

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	4849	41	113
DE	3620	16	166
ME	3434		
NE	2384		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Corn DDGS, > 6 and < 9% Oil

Corn DDGS is produced when the fat is centrifuged from the solubles before solubles are added to the distillers grains.

AAFCO #: 27.6, AAFCO 2010, p. 343

IFN #: 5-02-843

Proximate Components, %

	$\bar{x}$	n	SD
Dry matter	89.35	13	1.55
Crude protein	27.36	13	2.00
Crude fiber	8.92	4	1.38
Ether extract	8.90	8	0.46
Acid ether extract	8.71	4	0.16
Ash	4.04	9	1

Carbohydrate Components, %

	$\bar{x}$	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	9.63	4	2.95
Neutral detergent fiber	30.46	11	5.68
Acid detergent fiber	12.02	9	2.47
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility AID			Digestibility SID		
	$\bar{x}$	n	SD	$\bar{x}$	n	SD	$\bar{x}$	n	SD
Essential									
CP	27.36	13	2.00	64	40	5.19	74	35	5.83
Arg	1.23	6	0.16	74	40	5.02	81	40	5.25
His	0.74	6	0.08	74	40	4.97	78	40	4.75
Ile	1.06	9	0.09	72	40	5.03	76	40	4.87
Leu	3.25	9	0.44	82	40	4.09	84	40	4.00
Lys	0.90	9	0.13	55	40	10.76	61	40	8.75
Met	0.57	9	0.11	80	40	4.30	82	40	4.13
Phe	1.37	6	0.16	78	40	3.87	81	40	3.96
Thr	0.99	9	0.06	64	40	6.51	71	40	5.73
Trp	0.20	9	0.03	63	40	8.34	71	40	8.16
Val	1.39	9	0.12	71	40	5.16	75	40	4.95
Nonessential									
Ala	2.13	4	0.30	74	40	4.72	79	40	4.64
Asp	2.01	4	0.26	63	40	5.73	69	40	5.52
Cys	0.44	7	0.06	69	40	5.97	73	40	5.70
Glu	5.35	4	0.83	76	40	7.81	81	40	5.63
Gly	1.13	4	0.09	42	40	10.79	64	40	11.16
Pro	2.36	4	0.31	34	40	19.40	74	40	21.54
Ser	1.40	4	0.20	70	40	5.36	77	40	5.48
Tyr	1.22	3	0.16	78	20	4.48	81	20	3.98

Minerals

	$\bar{x}$	n	SD
Macro, %			
Ca	0.08	9	0.07
Cl	0.20		
K	0.88	4	0.11
Mg	0.49	4	0.24
Na	0.30	2	0.23
P	0.60	9	0.20
S	0.48	2	0.27
Micro, ppm			
Cr			
Cu	6.04	2	1.13
Fe	147	2	8.68
I			
Mn	16.51	2	2.98
Se	0.39		
Zn	51.62	2	16.11
Phytate P, %			
ATTD of P, %	60		
STTD of P, %	65		

Vitamins, mg/kg (unless otherwise noted)

	$\bar{x}$	n	SD
Fat Soluble			
β-Carotene	3.5		
Vitamin E			
Water Soluble			
Vitamin B_6	8.0		
Vitamin B_{12}, μg/kg	0		
Biotin	0.78		
Folacin	0.90		
Niacin	75		
Pantothenic acid	14.0		
Riboflavin	8.6		
Thiamin	2.9		
Choline	2637		

Energy, kcal/kg

	$\bar{x}$	n	SD
GE	4710	3	120
DE	3582	3	161
ME	3396		
NE	2343		

Fatty Acids, % of Ether Extract

	$\bar{x}$	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Corn DDGS, < 4% Oil

Corn DDGS is produced when fat is extracted from the DDGS using a solvent extraction process.

AAFCO #: 27.6, AAFCO 2010, p. 343

IFN #: 5-02-843

Proximate Components, %

	x̄	n	SD
Dry matter	89.25	2	2.20
Crude protein	27.86	2	4.73
Crude fiber	6.19	1	
Ether extract	3.57	2	0.62
Acid ether extract			
Ash	4.64	1	

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	10.00		
Neutral detergent fiber	33.75	2	1.20
Acid detergent fiber	16.91	1	
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	27.86	2	4.73	64	40	5.19	74	35	5.83
Arg	1.31	1		74	40	5.02	81	40	5.25
His	0.82	1		74	40	4.97	78	40	4.75
Ile	1.02	2	0.28	72	40	5.03	76	40	4.87
Leu	3.64	1		82	40	4.09	84	40	4.00
Lys	0.68	2	0.28	55	40	10.76	61	40	8.75
Met	0.50	2	0.12	80	40	4.30	82	40	4.13
Phe	1.69	1		78	40	3.87	81	40	3.96
Thr	0.97	2	0.18	64	40	6.51	71	40	5.73
Trp	0.18	2	0.01	63	40	8.34	71	40	8.16
Val	1.34	2	0.28	71	40	5.16	75	40	4.95
Nonessential									
Ala	2.13	1		74	40	4.72	79	40	4.64
Asp	1.84	1		63	40	5.73	69	40	5.52
Cys	0.51	2	0.04	69	40	5.97	73	40	5.70
Glu	4.26	1		76	40	7.81	81	40	5.63
Gly	1.18	1		42	40	10.79	64	40	11.16
Pro	2.11	1		34	40	19.40	74	40	21.54
Ser	1.30	1		70	40	5.36	77	40	5.48
Tyr	1.13	1		78	20	4.48	81	20	3.98

Minerals

	x̄	n	SD
Macro, %			
Ca	0.05	1	
Cl			
K			
Mg			
Na			
P	0.76	1	
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %	60		
STTD of P, %	65		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	5098	1	
DE	3291	2	269
ME	3102		
NE	2009		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	3.90		
C-12:0	0.00		
C-14:0	0.08		
C-16:0	8.33		
C-16:1	0.30		
C-18:0	1.35		
C-18:1	20.18		
C-18:2	42.38		
C-18:3	0.75		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	9.75		
MUFA	20.48		
PUFA	43.13		
IV	97.17		
IVP	37.90		

TABLE 17-1 Continued

Ingredient: Corn HP DDG
Corn is dehulled and degermed before it is fermented and distilled. The solubles are not added to the distilled grain. However, if the solubles are added to the dried grains, high protein distillers dried grains with solubles (HP-DDGS) is produced.
AAFCO #: 27.5, AAFCO 2010, p. 343
IFN #: 5-02-842

Proximate Components, %

	x̄	n	SD
Dry matter	91.20	7	2.04
Crude protein	45.35	6	4.32
Crude fiber	7.30	1	
Ether extract	3.54	5	0.69
Acid ether extract	3.70	1	
Ash	2.39	3	0.89

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	10.15	2	1.48
Neutral detergent fiber	33.63	3	7.06
Acid detergent fiber	20.63	3	6.02
Hemicellulose			
Acid detergent lignin	3.77	1	
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility AID			Digestibility SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	45.35	6	4.32	70	2	2.76	76	2	5.37
Arg	1.62	3	0.18	81	3	5.20	85	3	2.25
His	1.07	3	0.07	77	3	2.19	79	3	2.25
Ile	1.83	3	0.18	77	3	2.91	80	3	2.78
Leu	6.18	3	0.38	85	3	6.85	86	3	7.09
Lys	1.22	3	0.11	65	3	7.59	69	3	5.80
Met	0.93	3	0.12	85	3	2.70	86	3	2.87
Phe	2.42	3	0.12	82	3	4.97	84	3	5.01
Thr	1.59	3	0.09	70	3	2.27	75	3	2.25
Trp	0.24	3	0.03	76	3	4.95	82	3	3.29
Val	2.12	3	0.02	75	3	3.54	78	3	3.78
Nonessential									
Ala	3.32	3	0.2	80	3	5.43	82	3	5.43
Asp	2.75	3	0.26	71	3	1.34	74	3	1.72
Cys	0.82	3	0.04	75	3	2.86	78	3	3.72
Glu	7.52	3	0.58	82	3	5.94	83	3	6.03
Gly	1.39	3	0.07	55	3	9.22	70	3	4.27
Pro	3.65	3	0.06	64	3	15.64	79	3	5.51
Ser	1.96	3	0.12	79	3	2.87	82	3	2.85
Tyr	1.92	3	0.1	83	3	3.72	85	3	4.01

Minerals

	x̄	n	SD
Macro, %			
Ca	0.02	6	0.01
Cl			
K	0.37	1	
Mg	0.09	1	
Na	0.06	2	0.05
P	0.36	7	0.03
S	0.75	1	
Micro, ppm			
Cr			
Cu	2.03	1	
Fe	65.30	1	
I			
Mn	7.00	1	
Se			
Zn	27.30	1	
Phytate P, %	0.11	1	
ATTD of P, %	64	2	6.36
STTD of P, %	73	2	5.45

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	5173	3	162
DE	4040	3	351
ME	3732		
NE	2342		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Corn Distillers Solubles
AAFCO #: 27.4, AAFCO 2010, p. 342
IFN #: 5-02-844

Proximate Components, %	**x̄**	**n**	**SD**
Dry matter	87.80	1	
Crude protein	18.70	1	
Crude fiber			
Ether extract	12.07	1	
Acid ether extract			
Ash	8.70	1	

Carbohydrate Components, %	**x̄**	**n**	**SD**
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	5.27		
Neutral detergent fiber	24.80		
Acid detergent fiber	7.50		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	**Total**			**Digestibility AID**			**SID**		
	x̄	**n**	**SD**	**x̄**	**n**	**SD**	**x̄**	**n**	**SD**
Essential									
CP	18.70	1							
Arg	0.9	1							
His	0.6	1							
Ile	0.7	1							
Leu	1.8	1							
Lys	0.8	1							
Met	0.4	1							
Phe	0.8	1							
Thr	0.8	1							
Trp	0.2	1							
Val	1.1	1							
Nonessential									
Ala	1.3	1							
Asp	1.3	1							
Cys	0.4	1							
Glu	2.3	1							
Gly									
Pro	1.3	1							
Ser	0.8	1							
Tyr	0.6	1							

Minerals	**x̄**	**n**	**SD**
Macro, %			
Ca	0.29		
Cl	0.25		
K	1.50		
Mg	0.64		
Na	0.26		
P	1.24	1	
S	0.37		
Micro, ppm			
Cr			
Cu	83		
Fe	560		
I			
Mn	74		
Se	0.33		
Zn	85		
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	**x̄**	**n**	**SD**
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6	8.8		
Vitamin B_{12}, μg/kg	3		
Biotin	1.66		
Folacin	1.10		
Niacin	116		
Pantothenic acid	21.0		
Riboflavin	17.0		
Thiamin	6.9		
Choline	4842		

Energy, kcal/kg			
GE	4717		
DE	3325		
ME	3198		
NE	2312		

Fatty Acids, % of Ether Extract	**x̄**	**n**	**SD**
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Corn Germ
AAFCO #: 48.32, AAFCO 2010, p. 357

Proximate Components, %	x̄	n	SD
Dry matter	90.87	7	2.97
Crude protein	14.79	8	1.03
Crude fiber			
Ether extract	19.74	6	2.41
Acid ether extract	17.6	1	
Ash	5.54	5	1.30
Carbohydrate Components, %			
Lactose	0.00	3	0.00
Sucrose	0.00	3	0.00
Raffinose	0.00	3	0.00
Stachyose	0.00	3	0.00
Verbascose	0.00	3	0.00
Oligosaccharides			
Starch	23.51	4	2.58
Neutral detergent fiber	18.27	5	4.33
Acid detergent fiber	6.67	4	2.11
Hemicellulose			
Acid detergent lignin	2.37	1	
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	14.79	8	1.03	33	1		56	1	
Arg	1.11	3	0.03	79	2	8.73	87	2	5.02
His	0.42	3	0.01	65	2	7.55	72	2	4.03
Ile	0.43	3	0.03	51	2	9.46	61	2	6.22
Leu	1.05	3	0.07	61	2	3.93	69	2	0.64
Lys	0.78	3	0.02	56	2	12.76	64	2	8.63
Met	0.26	3	0.01	67	2	8.24	72	2	6.15
Phe	0.57	3	0.03	57	2	5.96	66	2	2.47
Thr	0.52	3	0.01	42	2	11.41	57	2	5.16
Trp	0.10	3	0.02	50	2	4.69	63	2	6.01
Val	0.72	3	0.02	57	2	11.16	67	2	6.93
Nonessential									
Ala	0.91	2	0	53	1		64	1	
Asp	1.10	2	0.06	47	1		60	1	
Cys	0.32	3	0.03	58	2	8.06	66	2	3.25
Glu	1.94	2	0.16	63	1		72	1	
Gly	0.77	2	0.01	14	1		76	1	
Pro	0.95	2	0.04	34	1		84	1	
Ser	0.59	2	0.04	48	1		65	1	
Tyr	0.41	3	0.02	51	2	7.52	61	2	3.11

Minerals	x̄	n	SD
Macro, %			
Ca	0.02	4	0.01
Cl			
K	1.53	1	
Mg	0.52	1	
Na	0.01	1	
P	1.27	5	0.13
S	0.17	1	
Micro, ppm			
Cr			
Cu	5.30	1	
Fe	96.7	1	
I			
Mn	22.30	1	
Se			
Zn	83.70	1	
Phytate P, %	1.07	1	
ATTD of P, %	33	2	6.15
STTD of P, %	37	2	4.95

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg	x̄	n	SD
GE	4919	1	
DE	3670	1	
ME	3569		
NE	2807		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Corn Germ Meal
AAFCO #: 48.22, AAFCO 2010, p. 357
IFN #: 5-02-894

Proximate Components, %

	x̄	n	SD
Dry matter	90.10	1	
Crude protein	23.33	2	3.19
Crude fiber	9.53	1	
Ether extract	2.12	1	
Acid ether extract	5.41	1	
Ash	2.96	2	0.78

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	14.20	1	
Neutral detergent fiber	44.46	2	14.07
Acid detergent fiber	10.75	2	0.54
Hemicellulose	43.28	1	
Acid detergent lignin	1.09	1	
Total dietary fiber	41.56	2	1.43
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	23.33	2	3.19	60					
Arg	1.49	1		76			83		
His	1.17	1		71			78		
Ile	0.64	1		66			75		
Leu	0.75	1		72			78		
Lys	1.70	1		53			62		
Met	1.04	1		77			80		
Phe	0.37	1		75			81		
Thr	0.89	1		59			70		
Trp	0.78	1		53			66		
Val	0.63	1		64			73		
Nonessential									
Ala	1.26	1		62			65		
Asp	1.50	1		60			65		
Cys	0.25			59			63		
Glu	0.33	1		62			65		
Gly	2.87	1		55			65		
Pro	0.91	1		59			65		
Ser	1.07	1		59			65		
Tyr	0.63	1		75			79		

Minerals

	x̄	n	SD
Macro, %			
Ca	0.03	1	
Cl			
K	0.54	1	
Mg	0.36	1	
Na			
P	0.90	1	
S	0.36	1	
Micro, ppm			
Cr			
Cu	7.03	1	
Fe			
I			
Mn	20.99	1	
Se			
Zn	133	1	
Phytate P, %			
ATTD of P, %	33		
STTD of P, %	37		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	4178	2	100
DE	2988		
ME	2830		
NE	1888		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	2.50		
C-12:0	0.00		
C-14:0	0.08		
C-16:0	8.33		
C-16:1	0.30		
C-18:0	1.35		
C-18:1	20.18		
C-18:2	42.38		
C-18:3	0.75		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	9.75		
MUFA	20.48		
PUFA	43.13		
IV	97.17		
IVP	24.29		

TABLE 17-1 Continued

Ingredient: Corn Gluten Feed
AAFCO #: 48.13, AAFCO 2010, p. 356
IFN #: 5-02-903

Proximate Components, %

	x̄	n	SD
Dry matter	87.13	4	2.89
Crude protein	17.39	4	3.82
Crude fiber	7.08	3	0.75
Ether extract	4.21	3	0.21
Acid ether extract			
Ash	5.14	4	0.72

Carbohydrate Components, %

	x̄	n	SD
Lactose	0.00	3	0.00
Sucrose	0.00	3	0.00
Raffinose	0.00	3	0.00
Stachyose	0.00	3	0.00
Verbascose	0.00	3	0.00
Oligosaccharides			
Starch	23.67	3	9.39
Neutral detergent fiber	27.50	4	3.06
Acid detergent fiber	8.43	4	2.22
Hemicellulose			
Acid detergent lignin			
Total dietary fiber	26.8	1	
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	17.39	4	3.82	64					
Arg	1.04			79			86		
His	0.67			69			75		
Ile	0.66			68			80		
Leu	1.96			81			85		
Lys	0.63			51			66		
Met	0.35			79			82		
Phe	0.76			80			85		
Thr	0.74			57			71		
Trp	0.07			47			66		
Val	1.01			71			77		
Nonessential									
Ala	1.28			80			84		
Asp	1.05			66			72		
Cys	0.46			53			62		
Glu	3.11			78			82		
Gly	0.79			52			62		
Pro	1.56			71			78		
Ser	0.78			68			76		
Tyr	0.58			80			84		

Minerals

	x̄	n	SD
Macro, %			
Ca	0.09	4	0.04
Cl	0.22		
K	0.98		
Mg	0.33		
Na	0.15		
P	0.78	4	0.15
S	0.22		
Micro, ppm			
Cr			
Cu	48		
Fe	460		
I			
Mn	24		
Se	0.27		
Zn	70		
Phytate P, %	0.62	2	0.01
ATTD of P, %	26	4	8.21
STTD of P, %	32	4	8.85

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene	1.0		
Vitamin E	8.5		
Water Soluble			
Vitamin B_6	13.0		
Vitamin B_{12}, μg/kg	0		
Biotin	0.14		
Folacin	0.28		
Niacin	66		
Pantothenic acid	17.0		
Riboflavin	2.4		
Thiamin	2.0		
Choline	1518		

Energy, kcal/kg

	x̄	n	SD
GE	3989	2	294
DE	2990		
ME	2872		
NE	2043		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	2.70		
C-12:0	0.00		
C-14:0	0.09		
C-16:0	9.99		
C-16:1	0.36		
C-18:0	1.62		
C-18:1	24.21		
C-18:2	50.85		
C-18:3	0.90		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	11.70		
MUFA	24.57		
PUFA	51.75		
IV	116.61		
IVP	31.48		

TABLE 17-1 Continued

Ingredient: Corn Gluten Meal
AAFCO #: 48.22, AAFCO 2010, p. 356
IFN #: 5-02-900

Proximate Components, %	x̄	n	SD
Dry matter	90.04	6	0.72
Crude protein	58.25	10	5.97
Crude fiber	0.70	4	0.13
Ether extract	4.74	5	1.97
Acid ether extract	0.63	1	
Ash	1.46	5	0.56
Carbohydrate Components, %			
Lactose	0.00	3	0.00
Sucrose	0.00	3	0.00
Raffinose	0.00	3	0.00
Stachyose	0.00	3	0.00
Verbascose	0.00	3	0.00
Oligosaccharides			
Starch	17.93	2	1.21
Neutral detergent fiber	1.57	2	0.05
Acid detergent fiber	7.08		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	58.25	10	5.97	72	6	20.43	75	6	20.11
Arg	1.66	8	0.46	88	6	2.10	91	6	2.00
His	1.32	8	0.33	86	6	2.94	87	6	3.07
Ile	2.23	8	0.33	91	6	1.48	93	6	1.55
Leu	9.82	7	0.98	96	6	1.17	96	6	1.22
Lys	0.93	8	0.18	77	6	4.79	81	6	4.78
Met	1.21	7	0.44	92	5	8.82	93	5	8.85
Phe	3.52	8	0.57	93	6	2.76	94	6	2.76
Thr	1.81	8	0.47	84	6	5.02	87	6	6.14
Trp	0.27	6	0.07	61	5	10.15	77		
Val	2.42	8	0.53	89	6	1.51	91	6	1.18
Nonessential									
Ala	4.33	5	1.11	92	5	3.59	93	5	3.24
Asp	2.97	5	0.82	86	5	2.05	89	5	2.70
Cys	1.01	6	0.29	86	4	2.30	88	4	3.13
Glu	11.20	5	2.99	93	5	2.73	94	5	2.74
Gly	1.28	5	0.37	78	5	13.22	89	5	14.31
Pro	4.93	5	1.25	78	5	15.81	86	5	14.54
Ser	2.29	5	0.87	91	5	2.23	93	5	3.51
Tyr	2.86	5	0.28	93	3	2.02	94	3	2.00

Minerals	x̄	n	SD
Macro, %			
Ca	0.03	2	0.00
Cl	0.06		
K	0.18	1	
Mg	0.09	1	
Na	0.02		
P	0.49	3	0.04
S	1.00	1	
Micro, ppm			
Cr			
Cu	11.04	1	
Fe	282		
I			
Mn	3.98	1	
Se	1.00		
Zn	25.97	1	
Phytate P, %			
ATTD of P, %	38	2	2.40
STTD of P, %	47	2	2.40

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	6.7		
Water Soluble			
Vitamin B_6	6.9		
Vitamin B_{12}, µg/kg	0		
Biotin	0.15		
Folacin	0.13		
Niacin	55		
Pantothenic acid	3.5		
Riboflavin	2.2		
Thiamin	0.3		
Choline	330		
Energy, kcal/kg			
GE	4865	5	324
DE	4133	4	124
ME	3737		
NE	2464		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	2.50		
C-12:0	0.00		
C-14:0	0.08		
C-16:0	8.88		
C-16:1	0.32		
C-18:0	1.44		
C-18:1	21.52		
C-18:2	45.20		
C-18:3	0.80		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	10.40		
MUFA	21.84		
PUFA	46.00		
IV	103.65		
IVP	25.91		

TABLE 17-1 Continued

Ingredient: Corn Grits, Hominy Feed
AAFCO #: No official definition
IFN #: 4-03-011

Proximate Components, %

	x̄	n	SD
Dry matter	87.47	6	0.98
Crude protein	9.12	6	0.91
Crude fiber	3.19	5	0.52
Ether extract	7.40	6	3.34
Acid ether extract			
Ash	2.34	5	0.58

Carbohydrate Components, %

	x̄	n	SD
Lactose	0.00	5	0.00
Sucrose	0.00	5	0.00
Raffinose	0.00	5	0.00
Stachyose	0.00	5	0.00
Verbascose	0.00	5	0.00
Oligosaccharides			
Starch	47.58	5	7.96
Neutral detergent fiber	14.30	4	0.22
Acid detergent fiber	4.51	4	0.34
Hemicellulose			
Acid detergent lignin			
Total dietary fiber	10.11	1	
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	9.12	6	0.91						
Arg	0.56						87		
His	0.28						80		
Ile	0.36						81		
Leu	0.98						86		
Lys	0.38						71		
Met	0.18						87		
Phe	0.43						86		
Thr	0.40						73		
Trp	0.10						68		
Val	0.52						80		
Nonessential									
Ala									
Asp									
Cys	0.18						74		
Glu									
Gly									
Pro									
Ser									
Tyr	0.40						88		

Minerals

	x̄	n	SD
Macro, %			
Ca	0.29	1	
Cl	0.07		
K	0.61		
Mg	0.24		
Na	0.08		
P	0.73	1	
S	0.03		
Micro, ppm			
Cr			
Cu	13.00		
Fe	67		
I			
Mn	15.00		
Se	0.10		
Zn	30.00		
Phytate P, %	0.49	1	
ATTD of P, %	26		
STTD of P, %	34		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene	9.0		
Vitamin E	6.5		
Water Soluble			
Vitamin B_6	11.0		
Vitamin B_{12}, μg/kg	0		
Biotin	0.13		
Folacin	0.21		
Niacin	47		
Pantothenic acid	8.2		
Riboflavin	2.1		
Thiamin	8.1		
Choline	1155		

Energy, kcal/kg

	x̄	n	SD
GE	4145	5	179
DE	3355		
ME	3293		
NE	2574		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	1.20		
C-12:0	0.08		
C-14:0	0.08		
C-16:0	11.25		
C-16:1	0.33		
C-18:0	1.50		
C-18:1	24.67		
C-18:2	41.83		
C-18:3	1.25		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	12.92		
MUFA	25.00		
PUFA	43.08		
IV	101.63		
IVP	12.20		

TABLE 17-1 Continued

Ingredient: Cottonseed, Full Fat
AAFCO #: 24.4, AAFCO 2010, p. 341
IFN #: 5-01-609

Proximate Components, %	x̄	n	SD
Dry matter	92.56	8	0.38
Crude protein	23.77	9	1.88
Crude fiber			
Ether extract	16.51	9	1.26
Acid ether extract			
Ash	4	9	0.28
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	2.30		
Neutral detergent fiber	51.04	9	3.77
Acid detergent fiber	38.59	9	2.9
Hemicellulose			
Acid detergent lignin	10.75	4	0.49
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total x̄	Total n	Total SD	AID x̄	AID n	AID SD	SID x̄	SID n	SID SD
Essential									
CP	23.77	9	1.88	73	17	5.18	77	17	5.16
Arg	2.41			87	20	3.73	88	20	3.77
His	0.61			72	20	8.93	74	20	8.36
Ile	0.7			67	20	9.32	70	20	9.46
Leu	1.18			70	20	7.90	73	20	7.76
Lys	0.87			59	20	10.87	63	20	10.85
Met	0.33			70	16	14.08	73	16	13.63
Phe	1.17			79	20	5.61	81	20	5.56
Thr	0.67			64	20	9.89	68	20	9.61
Trp	0.25			68	11	8.81	71	11	8.95
Val	0.98			69	20	8.45	73	20	8.23
Nonessential									
Ala	0.78			66	17	8.91	70	17	8.86
Asp	1.87			74	17	6.40	76	17	6.27
Cys	0.33			73	7	9.92	76	7	9.83
Glu	4.24			83	16	4.96	84	16	4.87
Gly	0.80			67	17	9.66	77	17	9.71
Pro	0.79			58	15	17.42	84	14	16.06
Ser	0.90			72	17	7.49	75	17	7.12
Tyr	0.56			73	16	6.39	76	14	6.24

Minerals	x̄	n	SD
Macro, %			
Ca	0.15	1	
Cl			
K			
Mg			
Na			
P	0.65	1	
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %	31		
STTD of P, %	36		

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg	x̄	n	SD
GE	5248		
DE	3207		
ME	3045		
NE	1970		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0	0.00		
C-14:0	0.94		
C-16:0	23.24		
C-16:1	0.71		
C-18:0	2.35		
C-18:1	18.22		
C-18:2	49.23		
C-18:3	0.19		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	26.53		
MUFA	18.93		
PUFA	49.42		
IV	106.69		
IVP	176.15		

TABLE 17-1 Continued

Ingredient: Cottonseed Meal
AAFCO #: 24.12, AAFCO 2010, p. 341
IFN #: 5-01-632

Proximate Components, %

	x̄	n	SD
Dry matter	90.69	8	1.87
Crude protein	39.22	25	3.59
Crude fiber	13.96	5	1.68
Ether extract	5.50	6	2.50
Acid ether extract			
Ash	6.39	5	0.46

Carbohydrate Components, %

	x̄	n	SD
Lactose	0.00	5	0.00
Sucrose	0.00	5	0.00
Raffinose	0.00	5	0.00
Stachyose	0.00	5	0.00
Verbascose	0.00	5	0.00
Oligosaccharides			
Starch	1.95	4	0.48
Neutral detergent fiber	25.15	4	4.07
Acid detergent fiber	17.92	5	1.99
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility AID			Digestibility SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	39.22	25	3.59	73	17	5.18	77	17	5.16
Arg	4.04	16	0.68	87	20	3.73	88	20	3.77
His	1.11	19	0.16	72	20	8.93	74	20	8.36
Ile	1.21	19	0.24	67	20	9.32	70	20	9.46
Leu	2.18	19	0.39	70	20	7.90	73	20	7.76
Lys	1.50	19	0.28	59	20	10.87	63	20	10.85
Met	0.51	15	0.14	70	16	14.08	73	16	13.63
Phe	1.98	19	0.32	79	20	5.61	81	20	5.56
Thr	1.36	19	0.18	64	20	9.89	68	20	9.61
Trp	0.53	13	0.16	68	11	8.81	71	11	8.95
Val	1.86	19	0.42	69	20	8.45	73	20	8.23
Nonessential									
Ala	1.51	13	0.31	66	17	8.91	70	17	8.86
Asp	3.28	14	0.78	74	17	6.40	76	17	6.27
Cys	0.82	12	0.31	73	7	9.92	76	7	9.83
Glu	6.93	14	1.56	83	16	4.96	84	16	4.87
Gly	1.58	14	0.32	67	17	9.66	77	17	9.71
Pro	1.50	11	0.43	58	15	17.42	84	14	16.06
Ser	1.80	14	0.61	72	17	7.49	75	17	7.12
Tyr	0.98	15	0.19	73	16	6.39	76	14	6.24

Minerals

	x̄	n	SD
Macro, %			
Ca	0.25	4	0.03
Cl	0.05		
K	1.40		
Mg	0.50		
Na	0.04		
P	0.98	6	0.09
S	0.31		
Micro, ppm			
Cr			
Cu	18.00		
Fe	184		
I			
Mn	20.00		
Se	0.80		
Zn	70.00		
Phytate P, %			
ATTD of P, %	31	5	9.98
STTD of P, %	36	5	8.99

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene	0.2		
Vitamin E	14.0		
Water Soluble			
Vitamin B_6	5.1		
Vitamin B_{12}, μg/kg	0		
Biotin	0.30		
Folacin	1.65		
Niacin	40		
Pantothenic acid	12.0		
Riboflavin	5.9		
Thiamin	7.0		
Choline	2933		

Energy, kcal/kg

	x̄	n	SD
GE	4383	5	148
DE	2912		
ME	2645		
NE	1624		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	4.77		
C-12:0	0.00		
C-14:0	0.88		
C-16:0	21.99		
C-16:1	0.67		
C-18:0	2.22		
C-18:1	17.25		
C-18:2	46.60		
C-18:3	0.19		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	25.09		
MUFA	17.92		
PUFA	46.79		
IV	101.04		
IVP	48.19		

TABLE 17-1 Continued

Ingredient: Egg, Whole, Spray Dried
AAFCO #: 9.74, AAFCO 2010, p. 331

Proximate Components, %

	x̄	n	SD
Dry matter	95.16	3	0.98
Crude protein	50.97	4	2.25
Crude fiber			
Ether extract	34.26	2	4.6
Acid ether extract	35.40	1	
Ash	5.75	1	

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber			
Acid detergent fiber			
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility AID			Digestibility SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	50.97	4	2.25						
Arg	3.01	3	0.01						
His	1.20	3	0.12						
Ile	2.81	3	0.21						
Leu	4.41	3	0.28						
Lys	3.54	3	0.15						
Met	1.62	3	0.09						
Phe	2.68	3	0.1						
Thr	2.13	3	0.03						
Trp	0.94	3	0.14						
Val	3.34	3	0.16						
Nonessential									
Ala	2.63	1							
Asp	4.65	1							
Cys	1.19	2	0.06						
Glu	5.92	1							
Gly	1.54	1							
Pro	1.57	1							
Ser	2.72	1							
Tyr	1.95	2	0.06						

Minerals

	x̄	n	SD
Macro, %			
Ca	0.29	2	0.11
Cl			
K			
Mg			
Na			
P	0.69	2	0.03
S			
Micro, ppm			
Cr			
Cu	1.80	1	
Fe	61	1	
I			
Mn	0.00	1	
Se			
Zn	43.70	1	
Phytate P, %			
ATTD of P, %	50	1	
STTD of P, %	55	1	

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	6283	2	202
DE			
ME			
NE			

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Feather Meal
AAFCO #: 9.15, AAFCO 2010, p. 327
IFN #: 5-03-795

Proximate Components, %

	x̄	n	SD
Dry matter	94.24	4	1.44
Crude protein	80.90	6	6.58
Crude fiber	0.32	1	
Ether extract	5.97	1	
Acid ether extract			
Ash	5.08	1	

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	0.00		
Neutral detergent fiber			
Acid detergent fiber	0.00		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	80.90	6	6.58	75	2	16.97	68	2	4.31
Arg	5.63	7	0.58	81	2	2.83	81	2	2.17
His	0.82	8	0.18	54	2	26.87	56	2	24.77
Ile	3.63	8	0.91	75	2	0.71	76	2	0.06
Leu	6.59	7	1.24	77	2	2.12	77	2	2.28
Lys	2.00	8	0.36	54	2	19.80	56	2	18.61
Met	0.59	5	0.13	65			73	1	
Phe	3.95	7	0.99	78	2	2.83	79	2	2.64
Thr	3.72	8	0.40	69	2	4.24	71	2	4.62
Trp	0.60	6	0.16	60	1		63	1	
Val	5.75	8	1.28	75	2	3.54	75	2	3.34
Nonessential									
Ala	3.90	4	0.44	70			71		
Asp	4.95	4	1.41	47			48		
Cys	4.32	4	0.44	71			73		
Glu	8.40	4	2.61	75	1		76	1	
Gly	7.08	4	1.50	78	1		80	1	
Pro	10.16	4	1.61	86			87		
Ser	8.18	4	2.66	76	1		77	1	
Tyr	2.12	6	0.55	73			79		

Minerals

	x̄	n	SD
Macro, %			
Ca	0.41	2	0.06
Cl	0.26		
K	0.19		
Mg	0.20		
Na	0.34		
P	0.28	3	0.10
S	1.39		
Micro, ppm			
Cr			
Cu	10.00		
Fe	76		
I			
Mn	10.00		
Se	0.69		
Zn	111		
Phytate P, %			
ATTD of P, %	74	2	1.91
STTD of P, %	89	2	2.33

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	7.3		
Water Soluble			
Vitamin B_6	3.0		
Vitamin B_{12}, μg/kg	78		
Biotin	0.13		
Folacin	0.20		
Niacin	21		
Pantothenic acid	10.0		
Riboflavin	2.1		
Thiamin	0.1		
Choline	891		

Energy, kcal/kg

	x̄	n	SD
GE	5467		
DE	3400		
ME	2850		
NE	1740		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	6.80		
C-12:0	0.00		
C-14:0	1.00		
C-16:0	17.40		
C-16:1	3.10		
C-18:0	6.90		
C-18:1	19.95		
C-18:2	1.65		
C-18:3	0.00		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	25.30		
MUFA	23.05		
PUFA	1.65		
IV	24.00		
IVP	16.32		

TABLE 17-1 Continued

Ingredient: Fish Meal, Combined
All fish meal data were combined because most citations did not distinguish between the species of fish.
AAFCO #:51.14, AAFCO 2010, p. 358
IFN #:5-01-977

Proximate Components, %

	x̄	n	SD
Dry matter	93.70	8	2.42
Crude protein	63.28	23	4.66
Crude fiber	0.24	4	0.22
Ether extract	9.71	5	1.28
Acid ether extract	8.73	1	
Ash	16.07	5	3.16

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	0.00		
Neutral detergent fiber			
Acid detergent fiber	0.00		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility AID			Digestibility SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	63.28	23	4.66	82	16	7.04	85	16	6.16
Arg	3.84	24	0.48	85	22	9.98	86	22	10.11
His	1.44	21	0.29	82	22	10.56	84	22	10.55
Ile	2.56	25	0.31	82	22	12.03	83	22	12.06
Leu	4.47	25	0.50	82	22	11.64	83	22	11.71
Lys	4.56	24	0.90	85	22	8.35	86	22	8.37
Met	1.73	22	0.45	86	18	7.53	87	18	7.57
Phe	2.47	24	0.22	80	22	12.37	82	22	12.43
Thr	2.58	25	0.33	78	21	14.37	81	22	14.49
Trp	0.63	16	0.10	73	10	9.43	76	10	9.97
Val	3.06	25	0.45	81	22	10.16	83	22	10.22
Nonessential									
Ala	3.93	18	0.54	79	15	14.67	80	15	14.65
Asp	5.41	17	1.18	71	15	22.27	73	15	22.53
Cys	0.61	16	0.20	62	11	18.94	64	11	17.71
Glu	7.88	17	1.18	79	15	14.48	80	15	14.54
Gly	4.71	18	0.98	71	15	20.64	75	15	20.63
Pro	2.89	18	1.07	65	14	25.52	86	14	21.49
Ser	2.43	18	0.59	72	15	20.75	75	15	20.96
Tyr	1.88	15	0.38	73	13	17.12	74	12	17.65

Minerals

	x̄	n	SD
Macro, %			
Ca	4.28	11	1.14
Cl			
K	0.62	2	0.10
Mg	0.13	1	
Na			
P	2.93	14	0.51
S			
Micro, ppm			
Cr			
Cu	8.00	1	
Fe	411	2	416
I			
Mn	38.90	1	
Se			
Zn	88.98	2	27.61
Phytate P, %			
ATTD of P, %	79	7	11.53
STTD of P, %	82	7	11.44

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	4496	4	84.4
DE	3958	3	392
ME	3528		
NE	2351		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Flaxseed
AAFCO #: No official definition

Proximate Components, %

	x̄	n	SD
Dry matter	92.13	3	1.49
Crude protein	22.53	7	1.53
Crude fiber	6.00	1	
Ether extract	33.77	5	4.41
Acid ether extract			
Ash	3.33	4	0.20

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber	39.65	2	11.38
Acid detergent fiber	24.85	2	6.86
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	22.53	7	1.53						
Arg	2.2	1							
His	0.51	1							
Ile	0.95	1					77		
Leu	1.35	1							
Lys	0.91	1					84		
Met	0.43	1					85		
Phe	1.08	1							
Thr	0.85	1					82		
Trp							86		
Val	1.16	1					77		
Nonessential									
Ala	1.05	1					77		
Asp	2.18	1					77		
Cys	0.41	1							
Glu	4.46	1					77		
Gly	1.38	1					77		
Pro	0.84	1					77		
Ser	1.06	1					77		
Tyr									

Minerals

	x̄	n	SD
Macro, %			
Ca	0.38		
Cl			
K			
Mg			
Na			
P	0.61		
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %	21		
STTD of P, %	28		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	6117	5	72
DE			
ME			
NE			

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	42.16		
C-12:0	0.00		
C-14:0	0.02		
C-16:0	5.14		
C-16:1	0.06		
C-18:0	3.15		
C-18:1	17.45		
C-18:2	14.00		
C-18:3	54.11		
C-18:4			
C-20:0	0.12		
C-20:1	0.16		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.12		
C-22:1	0.03		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.07		
SFA	8.63		
MUFA	17.70		
PUFA	68.11		
IV	189.20		
IVP	797.66		

TABLE 17-1 Continued

Ingredient: Flaxseed Meal
AAFCO #: 71.11, AAFCO 2010, p. 385
IFN #: 5-30-288

Proximate Components, %

	x̄	n	SD
Dry matter	90.18	4	1.43
Crude protein	33.28	8	1.79
Crude fiber	9.18	4	1.10
Ether extract	6.45	7	3.20
Acid ether extract			
Ash	5.23	5	0.55
Carbohydrate Components, %			
Lactose			
Sucrose	4.67	1	
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	5.17	2	5.48
Neutral detergent fiber	24.93	6	2.44
Acid detergent fiber	15.87	6	2.07
Hemicellulose			
Acid detergent lignin	5.89	1	
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	33.28	8	1.79	61	1		78	1	
Arg	3.00	3	0.58	80	3	8.01	82	3	9.23
His	0.67	3	0.03	69	3	4.02	74	3	4.48
Ile	1.33	3	0.02	74	3	10.15	79	3	10.59
Leu	1.91	3	0.08	73	3	8.19	78	3	8.47
Lys	1.19	3	0.07	65	3	6.14	77		
Met	0.77	3	0.27	74	3	1.41	82		
Phe	1.49	3	0.08	75	3	4.48	79	3	6.08
Thr	1.13	3	0.05	59	3	1.59	74		
Trp	0.51	3	0.14	57	3	27.71	78		
Val	1.55	3	0.05	68	3	3.50	75		
Nonessential									
Ala	1.45	2	0.01	72			75		
Asp	2.80	2	0.17	73			75	2	12.22
Cys	0.59	2	0.07	60	2	12.37	77		
Glu	6.15	2	0.04	73			75		
Gly	1.84	2	0.05	71			77	2	2.22
Pro	1.45	2	0.33	64	2	16.62	75		
Ser	1.39	2	0.04	71			76	2	5.86
Tyr	0.72	2	0.11	65	2	2.90	78		

Minerals

	x̄	n	SD
Macro, %			
Ca	0.37	4	0.03
Cl	0.06		
K	1.26		
Mg	0.50	3	0.04
Na	0.13		
P	0.87	5	0.05
S	0.39		
Micro, ppm			
Cr			
Cu	16.20	3	1.80
Fe	111	2	32.46
I			
Mn	45.90	3	0.90
Se	0.63		
Zn	57.90	3	6.32
Phytate P, %			
ATTD of P, %	21	1	
STTD of P, %	28	1	

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene	0.2		
Vitamin E	2.0		
Water Soluble			
Vitamin B_6	6.0		
Vitamin B_{12}, μg/kg	0		
Biotin	0.41		
Folacin	1.30		
Niacin	33		
Pantothenic acid	14.7		
Riboflavin	2.9		
Thiamin	7.5		
Choline	1512		

Energy, kcal/kg

	x̄	n	SD
GE	4887	2	175
DE	3060		
ME	2834		
NE	1830		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	3.00		
C-12:0	0.00		
C-14:0	0.08		
C-16:0	4.80		
C-16:1	0.08		
C-18:0	2.55		
C-18:1	14.03		
C-18:2	11.03		
C-18:3	40.65		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	7.43		
MUFA	14.10		
PUFA	51.68		
IV	143.79		
IVP	43.14		

TABLE 17-1 Continued

Ingredient: Gelatin
AAFCO #: 60.29, AAFCO 2010, p. 376
IFN #: 5-14-503

Proximate Components, %

	x̄	n	SD
Dry matter	87.54	3	2.53
Crude protein	100.1	1	
Crude fiber			
Ether extract	0.00		
Acid ether extract			
Ash			
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	0.00		
Neutral detergent fiber			
Acid detergent fiber	0.00		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	100.1	1		82	2	1.41	85	2	0.71
Arg	7.91	4	0.23	85			95	2	0.00
His	0.76	4	0.12	88	2	2.83	91	2	2.12
Ile	1.25	4	0.15	93	2	0.00	96	2	0.71
Leu	2.79	4	0.22	85	2	1.41	88	2	1.41
Lys	3.87	4	0.29	90	2	0.71	92	2	0.71
Met	0.97	4	0.06	91	2	0.71	92	2	0.71
Phe	1.89	4	0.16	91	2	0.71	93	2	1.41
Thr	2.17	4	0.85	78	2	1.41	81	2	1.41
Trp	0.09	4	0.09	93	2	0.71	98	2	1.41
Val	2.27	4	0.22	86	2	0.00	90	2	0.00
Nonessential									
Ala	8.99	3	0.37	87	2	0.71	88	2	0.71
Asp	4.73	3	1.62	63	2	11.31	66	2	11.31
Cys	0.11	4	0.06						
Glu	8.73	3	3.02	80	2	2.83	82	2	2.12
Gly	25.39	3	7.11	82	2	0.71	83	2	0.71
Pro	15.25	3	4.63	79	2	1.41	83	2	1.41
Ser	2.95	3	0.42	79	2	0.00	86		
Tyr	0.65	4	0.27	62	2	26.87	76	2	19.09

Minerals

	x̄	n	SD
Macro, %			
Ca			
Cl			
K			
Mg			
Na			
P			
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	5645		
DE	4900		
ME	4219		
NE	2519		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Kidney Beans, Extruded
AAFCO #:
IFN #:

Proximate Components, %

	x̄	n	SD
Dry matter	91.45	2	2.47
Crude protein	20.03	3	5.89
Crude fiber	4.42	2	2.95
Ether extract	1.10	2	0.59
Acid ether extract			
Ash	2.65	2	1.34

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber			
Acid detergent fiber			
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility AID			Digestibility SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	20.03	3	5.89	64	1		76	1	
Arg	1.28	1		84	1		94	1	
His	0.19	1		58	1		66	1	
Ile	0.94	1		66	1		72	1	
Leu	1.9	1		65	1		71	1	
Lys	1.51	1		82	1		85	1	
Met	0.25	1							
Phe	1.35	1		70	1		74	1	
Thr	0.94	1		67	1		76	1	
Trp									
Val	1.13	1		58	1		65	1	
Nonessential									
Ala	1	1		68	1		82	1	
Asp	2.08	1		86	1		89	1	
Cys	0.21	1							
Glu	2	1		83	1		87	1	
Gly	1.16	1		47	1		101	1	
Pro	0.77	1		45	1				
Ser	1.35	1		68	1		77	1	
Tyr	0.81	1		61	1		67	1	

Minerals

	x̄	n	SD
Macro, %			
Ca			
Cl			
K			
Mg			
Na			
P			
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, µg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

GE			
DE			
ME			
NE			

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Kidney Beans, Raw
AAFCO #:
IFN #:

Proximate Components, %	x̄	n	SD
Dry matter	86.6	1	
Crude protein	20.00	1	
Crude fiber	6.4	1	
Ether extract	1.35	1	
Acid ether extract			
Ash	3.5	1	

Carbohydrate Components, %	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber			
Acid detergent fiber			
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	20.00	1							
Arg	1.27	1							
His	0.2	1							
Ile	0.96	1							
Leu	1.9	1							
Lys	1.53	1							
Met	0.28	1							
Phe	1.31	1							
Thr	0.93	1							
Trp									
Val	1.15	1							
Nonessential									
Ala	1.02	1							
Asp	2.04	1							
Cys	0.24	1							
Glu	1.94	1							
Gly	1.12	1							
Pro	0.76	1							
Ser	1.36	1							
Tyr	0.8	1							

Minerals	x̄	n	SD
Macro, %			
Ca			
Cl			
K			
Mg			
Na			
P			
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg	x̄	n	SD
GE			
DE			
ME			
NE			

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	0.83		
C-12:0	0.00		
C-14:0	0.00		
C-16:0	12.77		
C-16:1	0.00		
C-18:0	1.69		
C-18:1	7.71		
C-18:2	21.45		
C-18:3	33.61		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	14.46		
MUFA	7.71		
PUFA	55.06		
IV	137.66		
IVP	11.43		

TABLE 17-1 Continued

Ingredient: Lentils
AAFCO #: No official definition
IFN #: 5-02-506

Proximate Components, %	x̄	n	SD
Dry matter	90.00	1	
Crude protein	26.00	1	
Crude fiber			
Ether extract	1.30		
Acid ether extract			
Ash	2.79	1	

Carbohydrate Components, %	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	41.75		
Neutral detergent fiber	17.37	1	
Acid detergent fiber	2.97	1	
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	26.00	1		73					
Arg	2.05			84			86		
His	0.78			76			79		
Ile	1.00			73			77		
Leu	1.84			73			76		
Lys	1.71			77			79		
Met	0.18			66			71		
Phe	1.29			72			75		
Thr	0.84			66			73		
Trp	0.21			62			68		
Val	1.27			70			75		
Nonessential									
Ala	1.24			69			73		
Asp	2.82			76			79		
Cys	0.27			57			66		
Glu	4.03			79			82		
Gly	1.11			67			75		
Pro	1.05			73			84		
Ser	1.13			72			78		
Tyr	0.70			73			77		

Minerals	x̄	n	SD
Macro, %			
Ca	0.10		
Cl	0.03		
K	0.89		
Mg	0.12		
Na	0.02		
P	0.38		
S	0.20		
Micro, ppm			
Cr			
Cu	10.00		
Fe	85		
I			
Mn	13.00		
Se	0.10		
Zn	25.00		
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene	1.0		
Vitamin E	0		
Water Soluble			
Vitamin B_6	5.5		
Vitamin B_{12}, μg/kg	0		
Biotin	0.13		
Folacin	0.70		
Niacin	22		
Pantothenic acid	14.9		
Riboflavin	2.4		
Thiamin	3.9		
Choline			

Energy, kcal/kg	x̄	n	SD
GE	4483		
DE	3540		
ME	3363		
NE	2437		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Lupins
AAFCO #: No official definition
IFN #: 5-27-717

Proximate Components, %

	x̄	n	SD
Dry matter	91.13	23	1.34
Crude protein	32.44	31	4.63
Crude fiber	14.25	2	2.91
Ether extract	6.08	20	1.14
Acid ether extract			
Ash	3.67	15	0.38

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	7.44	9	1.77
Neutral detergent fiber	24.11	22	2.88
Acid detergent fiber	19.90	22	3.08
Hemicellulose	3.70	5	0.72
Acid detergent lignin	1.52	14	0.75
Total dietary fiber			
Insoluble dietary fiber	30.03	1	
Soluble dietary fiber	1.61	1	

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	32.44	31	4.63	80	18	4.23	86	16	3.78
Arg	3.61	13	0.73	92	11	4.40	93	11	4.47
His	0.92	19	0.24	83	18	5.15	86	18	5.37
Ile	1.39	19	0.24	83	18	5.87	85	18	5.93
Leu	2.31	19	0.40	82	18	5.71	85	18	5.79
Lys	1.58	19	0.25	82	18	4.07	85	18	4.00
Met	0.21	19	0.07	75	18	8.95	81	18	7.95
Phe	1.34	19	0.24	82	18	5.99	84	18	6.12
Thr	1.20	18	0.15	76	18	5.78	82	18	6.00
Trp	0.26	14	0.08	78	13	3.94	82	11	4.40
Val	1.32	19	0.19	77	18	6.01	81	18	5.82
Nonessential									
Ala	1.14	13	0.18	72	11	7.35	78	11	7.31
Asp	3.26	13	0.65	81	11	9.36	85	11	9.42
Cys	0.46	17	0.09	78	16	7.93	83	18	7.91
Glu	7.00	13	1.57	86	11	7.97	88	11	7.83
Gly	1.38	13	0.23	70	11	7.81	80	11	8.25
Pro	1.37	13	0.21	67	11	14.04	93	11	6.91
Ser	1.61	13	0.33	80	11	8.16	84	11	8.13
Tyr	1.16	8	0.42	79	8	6.59	82	8	5.68

Minerals

	x̄	n	SD
Macro, %			
Ca	0.37	2	0.04
Cl	0.03		
K	1.10		
Mg	0.19		
Na	0.02		
P	0.31	9	0.05
S	0.24		
Micro, ppm			
Cr			
Cu	6.00		
Fe	54		
I			
Mn	1390		
Se	0.07		
Zn	32.00		
Phytate P, %	0.21	9	0.05
ATTD of P, %	50		
STTD of P, %	57		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	7.5		
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin	0.05		
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	4366	9	70
DE	3397	8	183
ME	3176		
NE	2043		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	9.74		
C-12:0	0.08		
C-14:0	0.13		
C-16:0	7.62		
C-16:1	0.35		
C-18:0	3.24		
C-18:1	36.53		
C-18:2	20.48		
C-18:3	4.58		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	2.62		
C-20:4			
C-20:5			
C-22:0			
C-22:1	0.95		
C-22:5			
C-22:6			
C-24:0			
SFA	11.08		
MUFA	40.45		
PUFA	25.06		
IV	85.62		
IVP	83.39		

TABLE 17-1 Continued

Ingredient: Meat and Bone Meal, P > 4%
Meat and bone meal was classified as containing greater than 4% P, but many of these products did not meet the AAFCO definition of the Ca level being less than 2.2 times the P level.

AAFCO #: 9.41, AAFCO 2010, p. 328
IFN #: 5-00-388

Proximate Components, %	x̄	n	SD
Dry matter	95.16	16	1.55
Crude protein	50.05	33	4.33
Crude fiber			
Ether extract	9.21	16	1.54
Acid ether extract			
Ash	31.95	20	5.59
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	0.00		
Neutral detergent fiber	32.50		
Acid detergent fiber	5.05	2	0.95
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	50.05	33	4.33	68	11	5.49	72	11	6.62
Arg	3.53	27	0.30	80	12	3.84	83	12	5.14
His	0.91	27	0.17	68	12	7.75	71	12	8.76
Ile	1.47	27	0.26	69	12	7.86	73	12	8.56
Leu	3.06	27	0.42	72	12	5.75	76	12	5.87
Lys	2.59	27	0.38	70	12	7.42	73	12	8.17
Met	0.69	21	0.18	81	4	4.35	84	4	2.90
Phe	1.65	27	0.22	76	12	5.91	79	12	5.98
Thr	1.63	27	0.28	64	12	7.07	69	12	8.00
Trp	0.30	26	0.06	52	10	10.82	62	10	13.17
Val	2.19	27	0.35	72	12	5.87	76	12	6.19
Nonessential									
Ala	3.87	13	0.44	76	6	1.94	79	6	3.66
Asp	3.74	13	0.64	61	6	4.82	65	6	6.49
Cys	0.46	20	0.15	46	4	28.55	56	4	24.15
Glu	6.09	13	0.89	71	6	3.39	75	6	5.23
Gly	7.06	13	0.68	74	6	4.91	78	6	5.88
Pro	4.38	13	0.62	70	4	6.43	81	4	3.87
Ser	1.89	13	0.32	66	6	4.22	71	6	6.84
Tyr	1.08	20	0.19	59	6	15.12	68	6	11.10

Minerals	x̄	N	SD
Macro, %			
Ca	10.94	28	1.79
Cl	0.69		
K	0.65		
Mg	0.41		
Na	0.63		
P	5.26	30	0.88
S	0.38		
Micro, ppm			
Cr			
Cu	11.00		
Fe	606		
I			
Mn	17.00		
Se	0.31		
Zn	96.00		
Phytate P, %			
ATTD of P, %	68	3	10.40
STTD of P, %	70	3	10.38

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	1.6		
Water Soluble			
Vitamin B_6	4.6		
Vitamin B_{12}, μg/kg	90		
Biotin	0.08		
Folacin	0.41		
Niacin	49		
Pantothenic acid	4.1		
Riboflavin	4.7		
Thiamin	0.4		
Choline	1996		
Energy, kcal/kg			
GE	3806	13	481
DE	3303	7	405
ME	2963		
NE	1961		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	10.60		
C-12:0	0.14		
C-14:0	1.89		
C-16:0	19.25		
C-16:1	2.59		
C-18:0	13.44		
C-18:1	28.49		
C-18:2	2.52		
C-18:3	0.63		
C-18:4	0.00		
C-20:0	1.05		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	35.77		
MUFA	31.08		
PUFA	3.15		
IV	34.47		
IVP	36.53		

TABLE 17-1 Continued

Ingredient: Meat Meal

Meat meal was classified containing less than 4% P, but many of these products did not meet the AAFCO definition of the Ca level being less than 2.2 times the P level.

AAFCO #: 9.40, AAFCO 2010, p. 328

IFN #: 5-00-385

Proximate Components, %

	x̄	n	SD
Dry matter	96.12	28	1.38
Crude protein	56.40	35	3.33
Crude fiber			
Ether extract	11.09	25	1.33
Acid ether extract			
Ash	21.59	29	3.6

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	0.00		
Neutral detergent fiber	31.6		
Acid detergent fiber	8.30		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	56.40	35	3.33	73	9	6.87	76	9	7.39
Arg	3.65	33	0.28	83	9	4.69	84	9	4.57
His	1.24	33	0.21	73	9	9.83	75	9	9.95
Ile	1.82	33	0.23	75	9	6.94	78	9	6.53
Leu	3.70	33	0.40	75	9	8.59	77	9	8.54
Lys	3.20	33	0.40	76	9	7.61	78	9	7.62
Met	0.83	30	0.13	80	6	7.19	82	6	6.73
Phe	1.98	33	0.27	77	9	7.12	79	9	7.12
Thr	1.89	33	0.20	71	9	7.32	74	9	7.49
Trp	0.40	30	0.06	67	4	12.47	76		
Val	2.61	33	0.31	74	9	8.69	76	9	8.51
Nonessential									
Ala	3.82	28	0.38	78	5	8.06	80	5	7.92
Asp	4.28	28	0.39	68	5	7.90	71	5	7.99
Cys	0.56	30	0.15	59	5	9.45	62	5	9.60
Glu	7.03	28	0.48	75	5	8.74	77	5	8.26
Gly	5.98	28	0.69	77	5	6.18	79	5	5.94
Pro	3.92	28	0.56	77	5	6.61	86	5	8.20
Ser	1.99	28	0.35	73	5	8.81	76	5	8.53
Tyr	1.35	30	0.13	77	6	7.38	78	6	8.18

Minerals

	x̄	N	SD
Macro, %			
Ca	6.37	37	1.43
Cl	0.97		
K	0.57		
Mg	0.35		
Na	0.80		
P	3.16	37	0.62
S	0.45		
Micro, ppm			
Cr			
Cu	10.00		
Fe	440		
I			
Mn	10.00		
Se	0.37		
Zn	94.00		
Phytate P, %			
ATTD of P, %	82	6	4.15
STTD of P, %	86	6	3.48

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	1.2		
Water Soluble			
Vitamin B_6	2.4		
Vitamin B_{12}, μg/kg	80		
Biotin	0.08		
Folacin	0.50		
Niacin	57		
Pantothenic acid	5.0		
Riboflavin	4.7		
Thiamin	0.6		
Choline	2077		

Energy, kcal/kg

	x̄	n	SD
GE	4497	26	251
DE	3452	14	424
ME	3068		
NE	2010		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Milk, Casein
AAFCO #: 54.16, AAFCO 2010, p. 361
IFN #: 5-01-162

Proximate Components, %

	x̄	n	SD
Dry matter	91.72	7	2.41
Crude protein	88.95	15	4.94
Crude fiber	0	1	
Ether extract	0.17	2	0.11
Acid ether extract			
Ash			

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	0.00		
Neutral detergent fiber			
Acid detergent fiber	0.00		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	88.95	15	4.94	87	13	8.96	94	13	6.11
Arg	3.13	17	0.20	88	14	11.52	95	14	5.45
His	2.57	17	0.32	93	15	4.89	97	15	3.42
Ile	4.49	17	0.48	91	15	5.37	95	15	3.40
Leu	8.24	17	0.51	94	15	4.09	97	15	3.01
Lys	6.87	17	0.57	95	15	4.08	97	15	2.76
Met	2.52	17	0.28	96	14	2.88	98	14	2.17
Phe	4.49	17	0.30	93	15	5.48	96	15	5.22
Thr	3.77	17	0.44	86	15	10.60	93	15	6.47
Trp	1.33	13	0.59	92	9	7.17	96	10	4.56
Val	5.81	17	0.53	92	15	5.01	96	15	3.42
Nonessential									
Ala	2.58	14	0.19	83	15	10.91	92	15	6.47
Asp	5.93	14	0.69	88	15	6.92	94	15	4.74
Cys	0.45	15	0.16	67	13	25.29	85	13	18.21
Glu	18.06	14	2.87	93	15	3.64	96	15	2.70
Gly	1.60	14	0.16	63	14	30.14	87	14	20.85
Pro	9.82	13	0.74	80	14	27.87	99	14	7.64
Ser	4.55	14	0.62	86	15	8.46	92	15	4.39
Tyr	4.87	12	0.36	94	14	4.26	97	14	3.64

Minerals

	x̄	n	SD
Macro, %			
Ca	0.20	3	0.17
Cl	0.04		
K	0.01		
Mg	0.01		
Na	0.01		
P	0.68	3	0.01
S	0.60		
Micro, ppm			
Cr			
Cu	4.00		
Fe	14		
I			
Mn	4.00		
Se	0.16		
Zn	30.00		
Phytate P, %			
ATTD of P, %	87	10	7.05
STTD of P, %	98		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6	0.4		
Vitamin B_{12}, µg/kg			
Biotin	0.04		
Folacin	0.51		
Niacin	1		
Pantothenic acid	2.7		
Riboflavin	1.5		
Thiamin	0.4		
Choline	205		

Energy, kcal/kg

	x̄	n	SD
GE	5670	1	
DE	4135		
ME	3530		
NE	2088		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Milk, Lactose
AAFCO #: No official definition
Lactose was treated as starch in the equation to calculate net energy.

Proximate Components, %	x̄	n	SD
Dry matter	95.00		
Crude protein	0.00		
Crude fiber			
Ether extract	0.00		
Acid ether extract			
Ash			
Carbohydrate Components, %			
Lactose	95.00		
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber			
Acid detergent fiber	0.00		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP									
Arg									
His									
Ile									
Leu									
Lys									
Met									
Phe									
Thr									
Trp									
Val									
Nonessential									
Ala									
Asp									
Cys									
Glu									
Gly									
Pro									
Ser									
Tyr									

Minerals	x̄	n	SD
Macro, %			
Ca			
Cl			
K			
Mg			
Na			
P			
S			
Micro, ppm			
Cr			
Cu	0.00	1	
Fe	5.80	1	
I			
Mn	0.00	1	
Se			
Zn	0.20	1	
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg	x̄	n	SD
GE	4143		
DE	3525		
ME	3525		
NE	2923		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Milk, Skim Milk Powder
AAFCO #: 54.3, AAFCO 2010, p. 360
IFN #: 5-01-175
Lactose was treated as starch in the equation to calculate net energy.

Proximate Components, %

	x̄	n	SD
Dry matter	94.60		
Crude protein	36.77	5	5.85
Crude fiber			
Ether extract	0.90		
Acid ether extract			
Ash			

Carbohydrate Components, %

	x̄	n	SD
Lactose	47.82		
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber			
Acid detergent fiber	0.00		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	36.77	5	5.85	86	6	3.33	90	6	3.00
Arg	1.17	5	0.21	90	7	5.41	95	7	5.05
His	0.94	5	0.14	91	7	5.48	93	7	5.42
Ile	1.45	5	0.34	89	7	7.05	91	7	6.77
Leu	3.02	5	0.29	92	7	3.01	94	7	2.94
Lys	2.42	4	0.28	92	7	4.35	94	7	4.53
Met	0.82	5	0.08	91	6	3.74	92	6	3.78
Phe	1.51	5	0.12	93	7	3.67	95	7	3.43
Thr	1.44	5	0.15	88	7	5.82	92	7	5.48
Trp	0.44			90			88		
Val	1.85	5	0.45	89	7	5.88	92	7	5.68
Nonessential									
Ala	1.19	3	0.15	85	3	4.36	90	3	4.17
Asp	2.67	3	0.16	88	3	0.54	91	3	0.47
Cys	0.33	2	0.10	81			86		
Glu	7.05	3	0.42	89	3	4.29	90	3	4.32
Gly	0.76	3	0.20	76	3	7.79	99	3	5.63
Pro	3.17	3	0.19	91	3	4.42	100		
Ser	1.81	3	0.02	82	3	10.74	85	3	10.73
Tyr	1.48	3	0.25	91	4	5.96	93	4	5.86

Minerals

	x̄	n	SD
Macro, %			
Ca	1.27	1	
Cl	1.00		
K	1.60		
Mg	0.12		
Na	0.48		
P	1.06	1	
S	0.32		
Micro, ppm			
Cr			
Cu	0.10	1	
Fe	0.00	1	
I			
Mn	0.00	1	
Se	0.12		
Zn	43.10	1	
Phytate P, %			
ATTD of P, %	91	1	
STTD of P, %	98		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	4.1		
Water Soluble			
Vitamin B_6	4.1		
Vitamin B_{12}, μg/kg	36		
Biotin	0.25		
Folacin	0.47		
Niacin	12		
Pantothenic acid	36.4		
Riboflavin	19.1		
Thiamin	3.7		
Choline	1393		

Energy, kcal/kg

	x̄	n	SD
GE	4437		
DE	3980		
ME	3730		
NE	2695		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	0.77		
C-12:0	1.82		
C-14:0	10.78		
C-16:0	30.52		
C-16:1	2.86		
C-18:0	11.04		
C-18:1	21.69		
C-18:2	2.47		
C-18:3	1.43		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	56.49		
MUFA	24.55		
PUFA	3.90		
IV	30.71		
IVP	2.36		

TABLE 17-1 Continued

Ingredient: Milk, Whey Permeate, 80% Lactose

Whey proteins are separated from the whey before dehydration. The product is a low-protein product containing primarily the lactose and ash from the whey.

AAFCO #: No official definition

Lactose was treated as starch in the equation to calculate net energy.

Proximate Components, %	x̄	n	SD
Dry matter	96.00		
Crude protein	3.50		
Crude fiber			
Ether extract	0.20		
Acid ether extract			
Ash			
Carbohydrate Components, %			
Lactose	80.00		
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber			
Acid detergent fiber	0.00		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP								1	
Arg									
His									
Ile									
Leu									
Lys									
Met									
Phe									
Thr									
Trp									
Val									
Nonessential									
Ala									
Asp									
Cys									
Glu									
Gly									
Pro									
Ser									
Tyr									

Minerals	x̄	n	SD
Macro, %			
Ca			
Cl			
K			
Mg			
Na			
P			
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			
Energy, kcal/kg			
GE	3426	1	
DE	3177	1	
ME	3153		
NE	2579		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Milk, Whey Permeate, 85% Lactose
Whey proteins are separated from the whey before dehydration. The product is a low-protein product containing primarily the lactose from whey. Most of the ash has been removed.
AAFCO #: No official definition
Lactose was treated as starch in the equation to calculate net energy.

Proximate Components, %				Amino Acids, %									
				Total				Digestibility					
	x̄	n	SD		x̄	n	SD	AID			SID		
Dry matter	98.00			Essential				x̄	n	SD	x̄	n	SD
Crude protein	3.00			CP									
Crude fiber				Arg									
Ether extract	0.20			His									
Acid ether extract				Ile									
Ash				Leu									
Carbohydrate Components, %				Lys									
				Met									
Lactose	85.00			Phe									
Sucrose				Thr									
Raffinose				Trp									
Stachyose				Val									
Verbascose				Nonessential									
Oligosaccharides				Ala									
Starch				Asp									
Neutral detergent fiber				Cys									
Acid detergent fiber	0.00			Glu									
Hemicellulose				Gly									
Acid detergent lignin				Pro									
Total dietary fiber				Ser									
Insoluble dietary fiber				Tyr									
Soluble dietary fiber													

Minerals				Vitamins, mg/kg (unless otherwise noted)				Fatty Acids, % of Ether Extract			
	x̄	n	SD		x̄	n	SD		x̄	n	SD
Macro, %				Fat Soluble				E.E.			
Ca	0.27	2	0.22	β-Carotene				C-12:0			
Cl				Vitamin E				C-14:0			
K				Water Soluble				C-16:0			
Mg				Vitamin B_6				C-16:1			
Na				Vitamin B_{12},μg/kg				C-18:0			
P	0.34	2	0.33	Biotin				C-18:1			
S				Folacin				C-18:2			
Micro, ppm				Niacin				C-18:3			
Cr				Pantothenic acid				C-18:4			
Cu				Riboflavin				C-20:0			
Fe				Thiamin				C-20:1			
I				Choline				C-20:4			
Mn								C-20:5			
Se								C-22:0			
Zn				**Energy, kcal/kg**				C-22:1			
								C-22:5			
Phytate P, %				GE	3657	1		C-22:6			
ATTD of P, %	82			DE	3626	1		C-24:0			
STTD of P, %	92			ME	3606			SFA			
				NE	2922			MUFA			
								PUFA			
								IV			
								IVP			

TABLE 17-1 Continued

Ingredient: Milk, Whey Powder
AAFCO #: 54.7, AAFCO 2010, p. 360
IFN #: 4-01-182
Lactose was treated as starch in the equation to calculate net energy.

Proximate Components, %	x̄	N	SD
Dry matter	97.15	4	0.82
Crude protein	11.55	6	0.93
Crude fiber	0.08	2	0.05
Ether extract	0.83	3	0.79
Acid ether extract			
Ash	8.00	2	0.44
Carbohydrate Components, %			
Lactose	72.88		
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber			
Acid detergent fiber	0.00		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	11.55	6	0.93	87	1		102	1	
Arg	0.26	7	0.02	83	2	13.57	98		
His	0.21	6	0.04	90	2	3.80	96		
Ile	0.64	8	0.04	94	2	3.26	96		
Leu	1.11	7	0.08	94	2	2.82	98		
Lys	0.88	8	0.09	94	2	2.61	97		
Met	0.17	8	0.00	95	2	6.26	98		
Phe	0.35	7	0.03	78	2	13.65	90		
Thr	0.71	8	0.04	85	2	2.35	89		
Trp	0.20	7	0.03	78			97		
Val	0.61	8	0.03	91	2	5.27	96		
Nonessential									
Ala	0.54	3	0.07	81			90		
Asp	1.16	3	0.10	83			91		
Cys	0.26	6	0.03	86			93		
Glu	1.95	3	0.14	85	2	10.91	90		
Gly	0.20	3	0.04	55			99		
Pro	0.66	2	0.07	74			100		
Ser	0.54	3	0.06	78			85		
Tyr	0.27	5	0.02	86	1		97	1	

Minerals	x̄	n	SD
Macro, %			
Ca	0.62	2	0.18
Cl	1.40		
K	1.96		
Mg	0.13		
Na	0.94		
P	0.69	4	0.04
S	0.72		
Micro, ppm			
Cr			
Cu	6.60	1	
Fe	57	1	
I			
Mn	3.00		
Se	0.12		
Zn	9.90	1	
Phytate P, %			
ATTD of P, %	82	4	1.80
STTD of P, %	92	4	1.56

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	0.3		
Water Soluble			
Vitamin B_6	4.0		
Vitamin B_{12}, μg/kg	23		
Biotin	0.27		
Folacin	0.85		
Niacin	10		
Pantothenic acid	47.0		
Riboflavin	27.1		
Thiamin	4.1		
Choline	1820		

Energy, kcal/kg	x̄	n	SD
GE	3647	1	
DE	3494	1	
ME	3415		
NE	2704		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	1.07		
C-12:0	1.12		
C-14:0	9.72		
C-16:0	30.47		
C-16:1	3.08		
C-18:0	9.07		
C-18:1	23.46		
C-18:2	2.34		
C-18:3	0.84		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	52.06		
MUFA	26.54		
PUFA	3.18		
IV	30.68		
IVP	3.28		

TABLE 17-1 Continued

Ingredient: Milk, Whey Protein Concentrate
AAFCO #: 54.25, AAFCO 2010, p. 361
IFN #: 5-06-836
Lactose was treated as starch in the equation to calculate net energy.

Proximate Components, %

	x̄	n	SD
Dry matter	94.40	8	1.72
Crude protein	76.32	7	4.61
Crude fiber	1.33	1	
Ether extract	0.20		
Acid ether extract			
Ash	2.63	8	0.44

Carbohydrate Components, %

	x̄	n	SD
Lactose	5.00		
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber			
Acid detergent fiber	0.00		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	76.32	7	4.61	84	2	4.95	86	2	4.78
Arg	2.01	8	0.21	88	3	4.36	93	3	4.11
His	1.46	8	0.21	86	3	3.79	92		
Ile	4.74	8	0.63	89	3	6.21	95		
Leu	8.43	8	1.15	90	3	5.73	95		
Lys	6.85	8	0.86	92	3	1.66	93	3	2.54
Met	1.65	8	0.28	91	3	4.59	96		
Phe	2.70	8	0.27	82	3	4.26	87		
Thr	4.82	8	0.69	83	3	1.63	85	3	3.00
Trp	1.59	8	0.21	88	3	4.71	95		
Val	4.54	8	0.50	90	3	2.42	95		
Nonessential									
Ala	3.77	8	0.37	86	3	3.17	90	3	3.37
Asp	7.80	8	0.88	89	3	3.59	91	3	4.02
Cys	1.79	8	0.35	84	3	4.80	85	3	4.68
Glu	12.29	8	1.79	88	3	4.41	89	3	4.56
Gly	1.45	8	0.11	72	3	17.70	87	3	10.37
Pro	4.29	8	0.83	81	3	3.75	93	3	2.63
Ser	3.28	8	0.50	85	3	2.01	88	3	2.62
Tyr	2.34	6	0.22	81	1		86	1	

Minerals

	x̄	n	SD
Macro, %			
Ca	0.63	1	
Cl			
K			
Mg			
Na			
P	0.38	1	
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %	82		
STTD of P, %	92		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	5245	1	
DE	4949	1	
ME	4430		
NE	2797		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Millet
AAFCO #: No official definition
IFN #: 4-03-120

Proximate Components, %	x̄	n	SD
Dry matter	88.50	1	
Crude protein	11.90	5	2.85
Crude fiber			
Ether extract	4.25	1	
Acid ether extract			
Ash			
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	54.95		
Neutral detergent fiber	15.80		
Acid detergent fiber	13.80		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber	4.78	1	
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	11.90	5	2.85	79	1		88	1	
Arg	0.57	4	0.09	82	1		89		
His	0.29	4	0.05	85	1		90	1	
Ile	0.49	4	0.08	83	1		89	1	
Leu	1.22	4	0.20	87	1		91	1	
Lys	0.37	4	0.05	74	1		83	1	
Met	0.28	4	0.05	72	1		75	1	
Phe	0.55	4	0.05	85	1		91	1	
Thr	0.45	4	0.07	75	1		86		
Trp	0.17	4	0.06	84	1		97		
Val	0.66	4	0.10	81	1		87	1	
Nonessential									
Ala	1.07	1		85	1		91	1	
Asp	1.09	1		79	1		86	1	
Cys	0.32	1		82	1		88		
Glu	2.84	1		89	1		92	1	
Gly	0.42	1		55			84		
Pro	0.80			81			95		
Ser	0.64	1		81	1		90		
Tyr	0.58	1		81	1		86		

Minerals	x̄	N	SD
Macro, %			
Ca	0.03		
Cl	0.03		
K	0.43		
Mg	0.16		
Na	0.04		
P	0.31		
S	0.14		
Micro, ppm			
Cr			
Cu	26.00		
Fe	71		
I			
Mn	30.00		
Se	0.70		
Zn	18.00		
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6	5.8		
Vitamin B_{12}, μg/kg	0		
Biotin	0.16		
Folacin	0.23		
Niacin	23		
Pantothenic acid	11.0		
Riboflavin	3.8		
Thiamin	7.3		
Choline	440		
Energy, kcal/kg			
GE	4472		
DE	3020		
ME	2939		
NE	2218		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	4.22		
C-12:0	0.07		
C-14:0	0.00		
C-16:0	12.51		
C-16:1	0.33		
C-18:0	3.65		
C-18:1	17.51		
C-18:2	47.75		
C-18:3	2.80		
C-18:4			
C-20:0	0.00		
C-20:1	0.47		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	16.23		
MUFA	18.32		
PUFA	50.55		
IV	110.52		
IVP	46.64		

TABLE 17-1 Continued

Ingredient: Molasses, Sugar Beets
AAFCO #: 63.1, AAFCO 2010, p. 380
IFN #: 4-30-289
Sucrose was treated as starch in the equation to calculate net energy.

Proximate Components, %

	x̄	n	SD
Dry matter	72.20		
Crude protein	10.00		
Crude fiber			
Ether extract	0.16		
Acid ether extract			
Ash			

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose	47.50		
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber			
Acid detergent fiber	0.08		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	10.00			86					
Arg	0.06						92		
His	0.04						90		
Ile	0.24			79			88		
Leu	0.24			74			89		
Lys	0.10			37			86		
Met	0.03			68			90		
Phe	0.06			46			90		
Thr	0.08			32			86		
Trp	0.05			44			86		
Val	0.15			59			87		
Nonessential									
Ala	0.23			79			95		
Asp	0.62			84			95		
Cys	0.05			44			84		
Glu	4.75			92			95		
Gly	0.20			58			95		
Pro	0.10						95		
Ser	0.21			66			95		
Tyr	0.24			81			91		

Minerals

	x̄	n	SD
Macro, %			
Ca	0.25		
Cl			
K			
Mg			
Na			
P	0.16		
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %	50		
STTD of P, %	63		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	3045	1	
DE	2366	1	
ME	2298		
NE	1795		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Molasses, Sugar Cane
AAFCO #: 63.7, AAFCO 2010, p. 380
IFN #: 4-13-251
Sucrose was treated as starch in the equation to calculate net energy.

Proximate Components, %

	x̄	n	SD
Dry matter	74.10		
Crude protein	4.80		
Crude fiber			
Ether extract	0.15		
Acid ether extract			
Ash			

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose	47.50		
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber			
Acid detergent fiber	0.15		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	4.80			77					
Arg	0.02						92		
His	0.01						90		
Ile	0.04			29			88		
Leu	0.06			25			89		
Lys	0.02						86		
Met	0.02			52			90		
Phe	0.03						90		
Thr	0.05						86		
Trp	0.01						86		
Val	0.11			51			87		
Nonessential									
Ala	0.20			72			95		
Asp	0.89			88			95		
Cys	0.04			40			84		
Glu	0.41			69			95		
Gly	0.07						95		
Pro	0.05						95		
Ser	0.07						95		
Tyr	0.03						91		

Minerals

	x̄	n	SD
Macro, %			
Ca	0.82	2	0.11
Cl			
K			
Mg			
Na			
P	0.08	2	0.02
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %	0.01		
ATTD of P, %	50		
STTD of P, %	63		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	4223		
DE	2366		
ME	2333		
NE	1842		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	0.10		
C-12:0	0.00		
C-14:0	0.00		
C-16:0	18.00		
C-16:1	0.00		
C-18:0	2.00		
C-18:1	32.00		
C-18:2	50.00		
C-18:3	0.00		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	20.00		
MUFA	32.00		
PUFA	50.00		
IV	119.25		
IVP	1.19		

TABLE 17-1 Continued

Ingredient: Oat Groats
AAFCO #: 69.1, AAFCO 2010, p. 383

Proximate Components, %	x̄	n	SD
Dry matter	87.10	1	
Crude protein	13.90	1	
Crude fiber			
Ether extract	5.90	1	
Acid ether extract			
Ash	2.40	1	
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	46.80	1	
Neutral detergent fiber	9.70	1	
Acid detergent fiber	6.50	1	
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	13.90	1							
Arg	0.85			86			86		
His	0.24			83			83		
Ile	0.55			83			83		
Leu	0.98			83			83		
Lys	0.48			79			79		
Met	0.20			85			86		
Phe	0.66			86			86		
Thr	0.44			76			80		
Trp	0.18			80			82		
Val	0.72			82			82		
Nonessential									
Ala	0.60								
Asp	1.04								
Cys	0.22			80			85		
Glu	2.59								
Gly	0.64								
Pro	0.69								
Ser	0.62								
Tyr	0.51			82			84		

Minerals	x̄	n	SD
Macro, %			
Ca	0.08		
Cl	0.09		
K	0.38		
Mg	0.11		
Na	0.05		
P	0.41		
S	0.20		
Micro, ppm			
Cr			
Cu	6.00		
Fe	49		
I			
Mn	32.00		
Se			
Zn			
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6	1.1		
Vitamin B_{12}, μg/kg	0		
Biotin	0.20		
Folacin	0.50		
Niacin	14		
Pantothenic acid	13.4		
Riboflavin	1.5		
Thiamin	6.5		
Choline	1139		

Energy, kcal/kg	x̄	n	SD
GE	4576		
DE	3690		
ME	3595		
NE	2720		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Oats
AAFCO #: No official definition
IFN #: 4-03-309

Proximate Components, %

	x̄	n	SD
Dry matter	89.88	5	1.75
Crude protein	11.16	5	1.44
Crude fiber			
Ether extract	5.42	4	0.84
Acid ether extract	4.20	1	
Ash	2.64	4	1.15

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	39.06	1	
Neutral detergent fiber	25.30	1	
Acid detergent fiber	13.73	4	1.21
Hemicellulose			
Acid detergent lignin			
Total dietary fiber	33.93	1	
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	11.16	5	1.44	62	1				
Arg	0.73	2	0.12	85	1		90		
His	0.24	2	0.04	81			85		
Ile	0.41	2	0.11	73	1		81	1	
Leu	0.79	2	0.16	75	1		83		
Lys	0.49	2	0.06	70			76		
Met	0.68	2	0.01	79			83		
Phe	0.52	2	0.12	81			84		
Thr	0.42	2	0.03	59			71		
Trp	0.14			59	1		75		
Val	0.63	2	0.13	72	1		80	1	
Nonessential									
Ala	0.46			67			76		
Asp	0.81			67			76		
Cys	0.36			69			75		
Glu	2.14			78			84		
Gly	0.48			61			77		
Pro	0.54			68			86		
Ser	0.47			69			81		
Tyr	0.41			76			82		

Minerals

	x̄	n	SD
Macro, %			
Ca	0.03	1	
Cl	0.10		
K	0.42		
Mg	0.16		
Na	0.08		
P	0.35	2	0.04
S	0.21		
Micro, ppm			
Cr			
Cu	6.00		
Fe	85		
I			
Mn	43.00		
Se	0.30		
Zn	38.00		
Phytate P, %	0.19	2	0
ATTD of P, %	33	3	3.10
STTD of P, %	39	3	3.53

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene	3.7		
Vitamin E	7.8		
Water Soluble			
Vitamin B_6	2.0		
Vitamin B_{12}, µg/kg	0		
Biotin	0.24		
Folacin	0.30		
Niacin	19		
Pantothenic acid	13.0		
Riboflavin	1.7		
Thiamin	6.0		
Choline	946		

Energy, kcal/kg

	x̄	n	SD
GE	4272	1	
DE	2627		
ME	2551		
NE	1893		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	6.90		
C-12:0	0.35		
C-14:0	0.22		
C-16:0	14.99		
C-16:1	0.19		
C-18:0	0.94		
C-18:1	31.38		
C-18:2	35.13		
C-18:3	1.61		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	16.49		
MUFA	31.57		
PUFA	36.74		
IV	96.36		
IVP	66.49		

TABLE 17-1 Continued

Ingredient: Oats, Naked
AAFCO #: No official definition
IFN #: 4-25-101

Proximate Components, %

	x̄	n	SD
Dry matter	91.80	3	0.26
Crude protein	14.70	3	3.48
Crude fiber	2.20	2	0.14
Ether extract	10.65	2	1.34
Acid ether extract	7.20	1	
Ash	1.73	3	0.29

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	56.35		
Neutral detergent fiber	11.07	3	2.73
Acid detergent fiber	3.70		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	14.70	3	3.48	73			81		
Arg	0.89	2	0.23	89	2	0.00	95	2	1.68
His	0.27	2	0.08	84	2	0.00	93		
Ile	0.54	2	0.16	83	2	1.41	89		
Leu	0.96	2	0.25	85	2	0.00	91	2	1.50
Lys	0.56	2	0.11	86	2	4.95	90		
Met	0.22	2	0.05	83	2	2.83	89		
Phe	0.65	2	0.19	87	2	0.00	92	2	1.59
Thr	0.48	2	0.12	78	2	0.71	85		
Trp	0.15			75			83		
Val	0.70	2	0.20	85	2	0.00	90		
Nonessential									
Ala	0.65	2	0.15	75			82		
Asp	1.09	2	0.31	75			82		
Cys	0.41	2	0.06	76	2	2.83	81	2	3.45
Glu	3.02	2	0.84	90	2	0.00	90		
Gly	0.63	2	0.13	68	2	2.83	83		
Pro	0.65	2	0.16	77			92		
Ser	0.70	2	0.18	77			88	2	1.28
Tyr	0.32	2	0.10	82	2	0.71	91		

Minerals

	x̄	n	SD
Macro, %			
Ca	0.08		
Cl	0.11		
K	0.36		
Mg	0.12		
Na	0.02		
P	0.38		
S	0.14		
Micro, ppm			
Cr			
Cu	4.00		
Fe	58		
I			
Mn	37.00		
Se	0.09		
Zn	34.00		
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	2.0		
Water Soluble			
Vitamin B_6	9.6		
Vitamin B_{12}, μg/kg	0		
Biotin	0.12		
Folacin	0.50		
Niacin	20		
Pantothenic acid	7.1		
Riboflavin	1.3		
Thiamin	5.2		
Choline	1240		

Energy, kcal/kg

	x̄	n	SD
GE	4422	2	34
DE	4126	2	69
ME	4026		
NE	3164		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Oats, Rolled, Dehulled
AAFCO #: No official definition

Proximate Components, %	x̄	n	SD
Dry matter	91.10	1	
Crude protein	12.94	1	
Crude fiber			
Ether extract	8.29	1	
Acid ether extract			
Ash			
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	51.02	1	
Neutral detergent fiber			
Acid detergent fiber			
Hemicellulose			
Acid detergent lignin			
Total dietary fiber	9.11	1	
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total x̄	Total n	Total SD	AID x̄	AID n	AID SD	SID x̄	SID n	SID SD
Essential									
CP	12.94	1							
Arg									
His									
Ile									
Leu									
Lys									
Met									
Phe									
Thr									
Trp									
Val									
Nonessential									
Ala									
Asp									
Cys									
Glu									
Gly									
Pro									
Ser									
Tyr									

Minerals	x̄	n	SD
Macro, %			
Ca			
Cl			
K			
Mg			
Na			
P			
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			
Energy, kcal/kg			
GE			
DE			
ME			
NE			

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Palm Kernel Expelled
Mechanical oil extraction from the oil palm fruit by screw pressing.
AAFCO #: No official definition

Proximate Components, %

	x̄	n	SD
Dry matter	92.00	2	3.39
Crude protein	16.64	2	0.22
Crude fiber	16.71	2	1.46
Ether extract	11.24	2	3.49
Acid ether extract			
Ash	3.82	2	0.08

Carbohydrate Components, %

	x̄	n	SD
Lactose	0.00	2	0.00
Sucrose	0.00	2	0.00
Raffinose	0.00	2	0.00
Stachyose	0.00	2	0.00
Verbascose	0.00	2	0.00
Oligosaccharides			
Starch	2.58	2	0.49
Neutral detergent fiber	56.48	2	9.04
Acid detergent fiber	37.31	2	4.24
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	16.64	2	0.22						
Arg									
His									
Ile									
Leu									
Lys									
Met									
Phe									
Thr									
Trp									
Val									
Nonessential									
Ala									
Asp									
Cys									
Glu									
Gly									
Pro									
Ser									
Tyr									

Minerals

	x̄	n	SD
Macro, %			
Ca	0.31	2	0.07
Cl			
K			
Mg			
Na			
P	0.52	2	0.01
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %	0.37	2	0.02
ATTD of P, %	39	2	0.64
STTD of P, %	49	2	0.50

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	3981	3	206
DE	3176	3	107
ME	3063		
NE	1941		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	8.50		
C-12:0	42.21		
C-14:0	14.13		
C-16:0	7.65		
C-16:1	0.00		
C-18:0	2.34		
C-18:1	13.41		
C-18:2	1.98		
C-18:3	0.36		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	73.35		
MUFA	13.41		
PUFA	2.34		
IV	16.62		
IVP	14.12		

TABLE 17-1 Continued

Ingredient: Palm Kernel Meal
Solvent oil extraction from the oil palm fruit.
AAFCO #: No official definition

Proximate Components, %	**x̄**	**n**	**SD**
Dry matter			
Crude protein	14.39	3	0.51
Crude fiber			
Ether extract			
Acid ether extract			
Ash			
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber			
Acid detergent fiber	35.0		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	**Total**			**Digestibility**					
				AID			**SID**		
	x̄	**n**	**SD**	**x̄**	**n**	**SD**	**x̄**	**n**	**SD**
Essential									
CP	14.39	3	0.51	51	2	7.24	63	2	7.78
Arg	1.41	3	0.31	80	2	4.62	84	2	4.24
His	0.26	3	0.02	58	2	7.23	65	2	7.07
Ile	0.55	3	0.03	57	2	4.37	63	2	4.24
Leu	0.90	3	0.04	67	2	4.88	73	2	4.95
Lys	0.36	3	0.08	35	2	11.65	48	2	9.90
Met	0.19	3	0.04	63	2	3.70	70	2	2.12
Phe	0.56	3	0.03	69	2	2.81	75	2	2.83
Thr	0.47	3	0.04	56	2	5.40	68	2	6.36
Trp	0.11	3	0.03	48			58		
Val	0.83	3	0.03	63	2	8.04	70	2	7.78
Nonessential									
Ala	0.60	3	0.03	57	2	4.08	68	2	4.24
Asp	1.22	3	0.10	59			65		
Cys	0.18	3	0.06	33	2	10.63	46	2	5.66
Glu	2.69	3	0.11	63	2	4.22	67	2	4.24
Gly	0.65	3	0.04	53			65	2	7.78
Pro	0.39	3	0.04	45			65		
Ser	0.85	3	0.32	55			65		
Tyr	0.34	3	0.02	49	2	1.44	57	2	1.41

Minerals	**x̄**	**n**	**SD**
Macro, %			
Ca	0.20	1	
Cl			
K			
Mg			
Na			
P	0.54	1	
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %	0.31	1	
ATTD of P, %	49	1	
STTD of P, %	58	1	

Vitamins, mg/kg (unless otherwise noted)	**x̄**	**n**	**SD**
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			
Energy, kcal/kg			
GE	3640	1	
DE	2970		
ME	2868		
NE	1641		

Fatty Acids, % of Ether Extract	**x̄**	**n**	**SD**
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Peanut Meal, Expelled
AAFCO #: 71.9, AAFCO 2010, p. 385
IFN #: 5-03-649

Proximate Components, %

	x̄	n	SD
Dry matter	92.00		
Crude protein	44.23	3	3.89
Crude fiber			
Ether extract	6.50		
Acid ether extract			
Ash			

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	6.65		
Neutral detergent fiber	14.6		
Acid detergent fiber	9.1		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility AID			Digestibility SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	44.23	3	3.89	79			87	3	3.78
Arg	5.20	3	0.37	93			93		
His	1.04	3	0.09	79			81		
Ile	1.46	3	0.08	78			81		
Leu	2.65	3	0.17	79			81		
Lys	1.55	3	0.10	73			76		
Met	0.50			80	4	4.08	83	4	4.44
Phe	2.12	3	0.17	86	4	4.56	88	4	4.85
Thr	1.16	3	0.06	70			74		
Trp	0.33	3	0.03	73			76		
Val	1.75	3	0.09	75			78	4	10.38
Nonessential									
Ala									
Asp									
Cys	0.60			78	1		81	1	
Glu									
Gly									
Pro									
Ser									
Tyr	1.74			88	2	3.11	92	1	

Minerals

	x̄	n	SD
Macro, %			
Ca	0.17		
Cl	0.03		
K	1.20		
Mg	0.33		
Na	0.06		
P	0.63		
S	0.29		
Micro, ppm			
Cr			
Cu	15		
Fe	285		
I			
Mn	39		
Se	0.28		
Zn	47		
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	2.7		
Water Soluble			
Vitamin B_6	7.4		
Vitamin B_{12}, μg/kg	0		
Biotin	0.35		
Folacin	0.70		
Niacin	166		
Pantothenic acid	47.0		
Riboflavin	5.2		
Thiamin	7.1		
Choline	1848		

Energy, kcal/kg

	x̄	n	SD
GE	4906		
DE	3895		
ME	3594		
NE	2381		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0	0.00		
C-14:0	0.00		
C-16:0	8.73		
C-16:1	0.00		
C-18:0	1.82		
C-18:1	39.82		
C-18:2	26.00		
C-18:3	0.00		
C-18:4			
C-20:0	0.00		
C-20:1	1.09		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	10.55		
MUFA	40.91		
PUFA	26.00		
IV	83.73		
IVP	54.42		

TABLE 17-1 Continued

Ingredient: Peanut Meal, Extracted
AAFCO #: 71.9, AAFCO 2010, p. 385
IFN #: 5-03-650

Proximate Components, %

	x̄	n	SD
Dry matter	91.80	1	
Crude protein	45.03	5	4.24
Crude fiber			
Ether extract	1.20		
Acid ether extract			
Ash			

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	6.70		
Neutral detergent fiber	16.20		
Acid detergent fiber	12.46		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	45.03	5	4.24	79			87	3	3.78
Arg	5.27	6	0.63	93			93		
His	0.98	6	0.17	79			81		
Ile	1.42	6	0.17	78			81		
Leu	2.61	6	0.25	79			81		
Lys	1.44	6	0.13	73			76		
Met	0.50	6	0.16	80	4	4.08	83	4	4.44
Phe	1.97	6	0.17	86	4	4.56	88	4	4.85
Thr	1.26	6	0.23	70			74		
Trp	0.40	4	0.05	73			76		
Val	1.58	6	0.27	75			78	4	10.38
Nonessential									
Ala	1.87	4	0.30	81			84		
Asp	4.49	4	1.40	86			87		
Cys	0.54	4	0.05	78	1		81	1	
Glu	7.51	4	2.42	88			89		
Gly	2.73	4	0.40	73			76		
Pro	1.52	4	0.82	87			92		
Ser	2.13	4	0.26	83			86		
Tyr	1.42	5	0.13	88	2	3.11	92	1	

Minerals

	x̄	n	SD
Macro, %			
Ca	0.39	2	0.16
Cl	0.04		
K	1.25		
Mg	0.31		
Na	0.07		
P	0.58	2	0.03
S	0.30		
Micro, ppm			
Cr			
Cu	15.00		
Fe	260		
I			
Mn	40.00		
Se	0.21		
Zn	41.00		
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	2.7		
Water Soluble			
Vitamin B_6	7.4		
Vitamin B_{12}, μg/kg	0		
Biotin	0.35		
Folacin	0.70		
Niacin	166		
Pantothenic acid	47.0		
Riboflavin	5.2		
Thiamin	7.1		
Choline	1848		

Energy, kcal/kg

	x̄	n	SD
GE	4622		
DE	3415		
ME	3109		
NE	1924		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Pea Protein Concentrate
Manufactured by air classification - processing technique that separates light from heavy particles in pulse flour.
AAFCO #: No official definition

Proximate Components, %				Amino Acids, %									
				Total				Digestibility					
	x̄	n	SD		x̄	n	SD	AID			SID		
Dry matter	94.31	1		Essential				x̄	n	SD	x̄	n	SD
Crude protein	82.82	1		CP	82.82	1		73	41	4.02	80	41	3.48
Crude fiber				Arg	6.46	1		87	39	4.35	90	39	3.28
Ether extract	8.04	1		His	1.96	1		78	45	4.37	82	45	3.65
Acid ether extract				Ile	3.73	1		76	45	5.10	81	45	3.62
Ash	6.22	1		Leu	6.57	1		77	45	4.39	81	45	4.16
Carbohydrate Components, %				Lys	5.78	1		82	45	2.91	85	45	2.72
				Met	0.80	1		72	39	4.08	77	39	3.78
Lactose				Phe	4.48	1		77	45	3.98	80	45	3.84
Sucrose				Thr	3.01	1		68	45	6.13	76	45	5.92
Raffinose				Trp	0.83	1		63	29	4.65	69	25	5.13
Stachyose				Val	4.06	1		72	45	5.60	78	45	4.60
Verbascose				Nonessential									
Oligosaccharides				Ala	3.39	1		70	39	5.15	77	39	4.25
Starch				Asp	9.36	1		78	39	3.53	82	39	3.41
Neutral detergent fiber				Cys	0.80	1		61	37	4.17	68	37	4.02
Acid detergent fiber	0.00			Glu	12.94	1		83	39	3.61	86	39	3.51
Hemicellulose				Gly	3.21	1		64	39	6.22	79	39	5.97
Acid detergent lignin				Pro	3.27	1		59	31	14.05	97	31	18.47
Total dietary fiber				Ser	4.06	1		73	39	5.55	79	39	4.64
Insoluble dietary fiber				Tyr									
Soluble dietary fiber													

Minerals				Vitamins, mg/kg (unless otherwise noted)				Fatty Acids, % of Ether Extract			
	x̄	n	SD		x̄	n	SD		x̄	n	SD
Macro, %				Fat Soluble				E.E.			
Ca				β-Carotene				C-12:0			
Cl				Vitamin E				C-14:0			
K				Water Soluble				C-16:0			
Mg				Vitamin B_6				C-16:1			
Na				Vitamin B_{12},µg/kg				C-18:0			
P				Biotin				C-18:1			
S				Folacin				C-18:2			
Micro, ppm				Niacin				C-18:3			
Cr				Pantothenic acid				C-18:4			
Cu				Riboflavin				C-20:0			
Fe				Thiamin				C-20:1			
I				Choline				C-20:4			
Mn								C-20:5			
Se								C-22:0			
Zn				**Energy, kcal/kg**				C-22:1			
								C-22:5			
Phytate P, %				GE	5562			C-22:6			
ATTD of P, %				DE	4620			C-24:0			
STTD of P, %				ME	4057			SFA			
				NE	2610			MUFA			
								PUFA			
								IV			
								IVP			

TABLE 17-1 Continued

Ingredient: Peas, Chick Peas
AAFCO #: No official definition

Proximate Components, %

	x̄	n	SD
Dry matter	89.74	3	1.15
Crude protein	20.33	3	0.89
Crude fiber			
Ether extract	4.14	2	0.23
Acid ether extract			
Ash	2.86	3	0.04

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	44.80		
Neutral detergent fiber	15.82	3	4.96
Acid detergent fiber	6.75	3	3.49
Hemicellulose	7.84	2	1.39
Acid detergent lignin	0.57	2	0.79
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	20.33	3	0.89	73	41	4.02	80	41	3.48
Arg	2.25	2	0.52	87	39	4.35	90	39	3.28
His	0.84	2	0.01	78	45	4.37	82	45	3.65
Ile	0.91	2	0.17	76	45	5.10	81	45	3.62
Leu	1.61	2	0.06	77	45	4.39	81	45	4.16
Lys	1.41	2	0.22	82	45	2.91	85	45	2.72
Met	0.30	2	0.00	72	39	4.08	77	39	3.78
Phe	1.23	2	0.08	77	45	3.98	80	45	3.84
Thr	0.91	2	0.05	68	45	6.13	76	45	5.92
Trp									
Val	1.02	2	0.08	72	45	5.60	78	45	4.60
Nonessential									
Ala	0.59	2	0.00	70	39	5.15	77	39	4.25
Asp	2.50	2	0.05	78	39	3.53	82	39	3.41
Cys	0.44	2	0.00	61	37	4.17	68	37	4.02
Glu	3.12	2	0.08	83	39	3.61	86	39	3.51
Gly	0.99	2	0.05	64	39	6.22	79	39	5.97
Pro									
Ser	1.06	2	0.02	73	39	5.55	79	39	4.64
Tyr	0.82	2	0.10	74	32	5.62	78	31	4.96

Minerals

	x̄	n	SD
Macro, %			
Ca			
Cl			
K			
Mg			
Na			
P			
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	4554		
DE	3504		
ME	3366		
NE	2491		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	6.04		
C-12:0	0.00		
C-14:0	0.15		
C-16:0	8.29		
C-16:1	0.20		
C-18:0	1.41		
C-18:1	22.28		
C-18:2	42.93		
C-18:3	1.67		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	9.85		
MUFA	22.48		
PUFA	44.60		
IV	102.49		
IVP	61.91		

TABLE 17-1 Continued

Ingredient: Peas, Cow Peas
AAFCO #: No official definition

Proximate Components, %	x̄	n	SD
Dry matter	88.10		
Crude protein	22.19		
Crude fiber			
Ether extract	1.20		
Acid ether extract			
Ash			

Carbohydrate Components, %	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	43.46		
Neutral detergent fiber			
Acid detergent fiber	6.75		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility AID			Digestibility SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	22.19			73	41	4.02	80	41	3.48
Arg									
His									
Ile									
Leu									
Lys									
Met									
Phe									
Thr									
Trp									
Val									
Nonessential									
Ala									
Asp									
Cys									
Glu									
Gly									
Pro									
Ser									
Tyr									

Minerals	x̄	n	SD
Macro, %			
Ca			
Cl			
K			
Mg			
Na			
P			
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg	x̄	n	SD
GE	4417		
DE	3504		
ME	3353		
NE	2420		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	1.26		
C-12:0	0.08		
C-14:0	0.24		
C-16:0	20.16		
C-16:1	0.32		
C-18:0	4.21		
C-18:1	6.98		
C-18:2	27.22		
C-18:3	15.79		
C-18:4			
C-20:0	0.00		
C-20:1	0.08		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	24.68		
MUFA	7.38		
PUFA	43.02		
IV	99.83		
IVP	12.58		

TABLE 17-1 Continued

Ingredient: Peas, Field Peas
AAFCO #: No official definition

Proximate Components, %

	x̄	n	SD
Dry matter	88.10	28	2.67
Crude protein	22.17	61	1.51
Crude fiber	6.16	20	0.92
Ether extract	1.20	35	0.48
Acid ether extract			
Ash	2.86	34	0.18

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose	0.19	9	0.58
Raffinose	0.04	9	0.13
Stachyose	0.23	9	0.68
Verbascose	0.32	9	0.96
Oligosaccharides			
Starch	43.46	30	3.72
Neutral detergent fiber	12.84	30	3.90
Acid detergent fiber	6.90	24	1.50
Hemicellulose	2.79	6	0.84
Acid detergent lignin	0.45	10	0.51
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	22.17	61	1.51	73	41	4.02	80	41	3.48
Arg	1.91	53	0.36	87	39	4.35	90	39	3.28
His	0.53	59	0.05	78	45	4.37	82	45	3.65
Ile	0.94	59	0.12	76	45	5.10	81	45	3.62
Leu	1.56	59	0.14	77	45	4.39	81	45	4.16
Lys	1.63	61	0.18	82	45	2.91	85	45	2.72
Met	0.21	59	0.03	72	39	4.08	77	39	3.78
Phe	1.02	58	0.10	77	45	3.98	80	45	3.84
Thr	0.83	59	0.10	68	45	6.13	76	45	5.92
Trp	0.21	47	0.08	63	29	4.65	69	25	5.13
Val	1.03	59	0.10	72	45	5.60	78	45	4.60
Nonessential									
Ala	0.95	49	0.11	70	39	5.15	77	39	4.25
Asp	2.56	49	0.27	78	39	3.53	82	39	3.41
Cys	0.31	57	0.04	61	37	4.17	68	37	4.02
Glu	3.87	49	0.54	83	39	3.61	86	39	3.51
Gly	0.95	49	0.11	64	39	6.22	79	39	5.97
Pro	0.94	29	0.19	59	31	14.05	97	31	18.47
Ser	1.05	48	0.15	73	39	5.55	79	39	4.64
Tyr	0.59	46	0.13	74	32	5.62	78	31	4.96

Minerals

	x̄	n	SD
Macro, %			
Ca	0.09	10	0.04
Cl			
K			
Mg			
Na			
P	0.42	13	0.06
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %	0.17	7	0.07
ATTD of P, %	49	8	6.13
STTD of P, %	56	7	5.65

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	4035	4	54
DE	3504	2	21
ME	3353		
NE	2419		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Peas, Field Pea Splits
AAFCO #: No official definition

Proximate Components, %	x̄	n	SD
Dry matter	88.10		
Crude protein	22.19		
Crude fiber			
Ether extract	1.20		
Acid ether extract			
Ash			
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	43.46		
Neutral detergent fiber			
Acid detergent fiber	6.90		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility AID			Digestibility SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	22.19			73	41	4.02	80	41	3.48
Arg									
His									
Ile									
Leu									
Lys									
Met									
Phe									
Thr									
Trp									
Val									
Nonessential									
Ala									
Asp									
Cys									
Glu									
Gly									
Pro									
Ser									
Tyr									

Minerals	x̄	n	SD
Macro, %			
Ca	0.10	1	
Cl			
K			
Mg			
Na			
P	0.43	1	
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %	49		
STTD of P, %	56		

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			
Energy, kcal/kg			
GE	4417		
DE	3504		
ME	3353		
NE	2419		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Pet Food Byproduct
AAFCO #:T60.108, AAFCO 2010, p. 379

Proximate Components, %	x̄	n	SD
Dry matter	92.80	1	
Crude protein	20.94	1	
Crude fiber	1.70	1	
Ether extract	8.29	1	
Acid ether extract			
Ash	5.65	1	
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber			
Acid detergent fiber			
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	20.94	1							
Arg	1.60	1							
His	0.53	1							
Ile	0.90	1							
Leu	1.59	1							
Lys	1.25	1							
Met	0.45	1							
Phe	0.97	1							
Thr	0.82	1							
Trp									
Val	1.05	1							
Nonessential									
Ala	1.28	1							
Asp	1.89	1							
Cys	0.09	1							
Glu	3.66	1							
Gly	1.60	1							
Pro	1.20	1							
Ser	0.89	1							
Tyr									

Minerals	x̄	n	SD
Macro, %			
Ca	0.82	1	
Cl	0.32	1	
K	0.74	1	
Mg	0.15	1	
Na	0.22	1	
P	0.84	1	
S			
Micro, ppm			
Cr			
Cu	4.40	1	
Fe	152	1	
I			
Mn	85.80	1	
Se			
Zn	293	1	
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			
Energy, kcal/kg			
GE	4601	1	
DE			
ME			
NE			

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Porcine Solubles, Dried
AAFCO #: 9.12, AAFCO 2010, p. 327
IFN #: 5-00-393

Proximate Components, %

	x̄	n	SD
Dry matter			
Crude protein	51.01	1	
Crude fiber			
Ether extract			
Acid ether extract			
Ash			

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber			
Acid detergent fiber			
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	51.01	1							
Arg	2.72	1							
His	1.06	1							
Ile	2.06	1							
Leu	3.94	1							
Lys	3.81	1							
Met	0.96	1							
Phe	2.23	1							
Thr	2.10	1							
Trp	0.25	1							
Val	2.60	1							
Nonessential									
Ala	2.95	1							
Asp									
Cys	0.78	1							
Glu									
Gly	3.65	1							
Pro	2.83	1							
Ser	1.86	1							
Tyr	1.86	1							

Minerals

	x̄	n	SD
Macro, %			
Ca			
Cl			
K			
Mg			
Na			
P			
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE			
DE			
ME			
NE			

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Potato Protein Concentrate
AAFCO #: 60.94, AAFCO 2010, p. 378
IFN #: 5-25-392

Proximate Components, %

	x̄	n	SD
Dry matter	93.39	2	1.84
Crude protein	79.80	2	1.91
Crude fiber	1.43	2	1.40
Ether extract	2.78	2	1.74
Acid ether extract			
Ash	1.28	2	1.07

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber			
Acid detergent fiber			
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	79.80	2	1.91	85	2	2.83	87	2	2.78
Arg	4.14	2	0.11	91	2	1.41	92	2	1.38
His	1.76	2	0.07	87	2	2.83	88	2	2.79
Ile	4.18	2	0.52	87	2	2.12	87	2	2.02
Leu	8.14	2	0.03	89	2	2.12	89	2	2.12
Lys	6.18	2	0.13	88	2	2.12	88	2	2.11
Met	1.74	2	0.05	90	2	1.41	91	2	1.39
Phe	5.10	2	0.01	82	2	2.12	82	2	2.12
Thr	4.61	2	0.04	84	2	2.83	85	2	2.82
Trp	1.10	2	0.00	78	2	3.54	79	2	3.54
Val	5.36	2	0.10	88	2	2.12	88	2	2.10
Nonessential									
Ala	4.02	2	0.18	86	2	2.12	87	2	2.05
Asp	9.99	2	0.28	84	2	4.24	85	2	4.22
Cys	1.13	2	0.03	65	2	4.24	67	2	4.29
Glu	8.65	2	0.26	86	2	3.54	87	2	3.50
Gly	4.08	2	0.01	85	2	4.24	89	2	4.23
Pro	4.06	2	0.01	88	2	1.41	100	2	1.37
Ser	4.35	2	0.08	86	2	2.83	87	2	2.85
Tyr	3.93			78			85		

Minerals

	x̄	n	SD
Macro, %			
Ca			
Cl			
K			
Mg			
Na			
P			
S			
Micro, ppm			
Cr			
Cu	38.50	1	
Fe	128	1	
I			
Mn	0.10	1	
Se			
Zn	14.30	1	
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	5439		
DE	4140		
ME	3597		
NE			

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	0.90		
C-12:0	0.00		
C-14:0	0.32		
C-16:0	13.76		
C-16:1	0.40		
C-18:0	3.12		
C-18:1	1.28		
C-18:2	23.36		
C-18:3	16.56		
C-18:4	0.00		
C-20:0	0.80		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.48		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	18.48		
MUFA	1.68		
PUFA	39.92		
IV	89.11		
IVP	8.02		

TABLE 17-1 Continued

Ingredient: Poultry Byproduct
AAFCO #: 9.14, AAFCO 2010, p. 327
IFN #: 5-03-800

Proximate Components, %

	$\bar{x}$	n	SD
Dry matter	92.08	7	3.69
Crude protein	64.03	11	2.35
Crude fiber	0.35	2	0.21
Ether extract	12.02	3	1.08
Acid ether extract	18.30	2	1.27
Ash	13.32	5	2.25
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	0.00		
Neutral detergent fiber			
Acid detergent fiber	0.00		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	$\bar{x}$	n	SD	$\bar{x}$	n	SD	$\bar{x}$	n	SD
Essential									
CP	64.03	11	2.35	75	5	2.71	78	5	2.14
Arg	4.35	11	0.26	87	5	2.48	89	5	1.91
His	1.28	11	0.09	80	5	4.97	82	5	3.92
Ile	2.38	11	0.13	79	5	1.96	81	5	1.49
Leu	4.42	11	0.21	80	5	4.41	82	5	3.05
Lys	3.69	11	0.31	84	5	5.08	85	2	4.07
Met	1.25	7	0.12	74			77		
Phe	2.23	11	0.19	82	5	3.79	84	5	3.15
Thr	2.35	11	0.25	74	5	3.95	77	5	2.59
Trp	0.46	9	0.12	74	5	13.02	78	5	9.46
Val	2.91	11	0.39	78	5	2.45	80	5	2.17
Nonessential									
Ala	3.75	3	1.02	78	1		81	1	
Asp	4.11	3	0.09	59	1		63	1	
Cys	0.63	5	0.38	70			72		
Glu	6.41	3	1.33	75	1		78	1	
Gly	6.17	4	2.25	75	1		79	1	
Pro	3.91	4	1.98	75	1		81	1	
Ser	2.27	4	0.28	72	1		76	1	
Tyr	1.93	5	0.24	51	1		69		

Minerals

	$\bar{x}$	n	SD
Macro, %			
Ca	4.54	8	0.41
Cl	0.49		
K	0.53		
Mg	0.18		
Na	0.49		
P	2.51	8	0.18
S	0.52		
Micro, ppm			
Cr			
Cu	10.00		
Fe	442		
I			
Mn	9.00		
Se	0.88		
Zn	94.00		
Phytate P, %			
ATTD of P, %	48		
STTD of P, %	53		

Vitamins, mg/kg (unless otherwise noted)

	$\bar{x}$	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6	4.4		
Vitamin B_{12}, μg/kg			
Biotin	0.09		
Folacin	0.50		
Niacin	47		
Pantothenic acid	11.1		
Riboflavin	10.5		
Thiamin	0.2		
Choline	6029		

Energy, kcal/kg

	$\bar{x}$	n	SD
GE	5300	2	112
DE	3090		
ME	2655		
NE	1774		

Fatty Acids, % of Ether Extract

	$\bar{x}$	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Poultry Meal
AAFCO #: 9.71, AAFCO 2010, p. 331
IFN #: 5-03-798

Proximate Components, %	x̄	n	SD
Dry matter	96.20	1	
Crude protein	64.72	5	4.54
Crude fiber			
Ether extract			
Acid ether extract	14.40	1	
Ash	12.06	3	1.32

Carbohydrate Components, %	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber			
Acid detergent fiber			
Hemicellulose			
Acid detergent lignin			
Total dietary fiber	2.60	1	
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility: AID			Digestibility: SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	64.72	5	4.54						
Arg	4.46	2	0.36						
His	1.69	2	0.06						
Ile	2.50	5	0.16						
Leu	4.63	5	0.23						
Lys	3.99	5	0.6						
Met	1.15	5	0.23						
Phe	2.64	2	0.07						
Thr	2.55	5	0.25						
Trp	0.62	4	0.1						
Val	3.07	5	0.13						
Nonessential									
Ala	4.18	2	0.07						
Asp	5.71	2	0.49						
Cys	0.87	5	0.25						
Glu	8.80	2	0.75						
Gly	5.79	2	0.7						
Pro	4.23	1							
Ser	3.67	2	0.83						
Tyr	1.84	2	0.26						

Minerals	x̄	n	SD
Macro, %			
Ca	2.82	3	0.28
Cl			
K			
Mg			
Na			
P	1.94	3	0.14
S			
Micro, ppm			
Cr			
Cu	35.70	1	
Fe	230	1	
I			
Mn	5.20	1	
Se			
Zn	99.40	1	
Phytate P, %			
ATTD of P, %	49	1	
STTD of P, %	62	1	

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg			
GE			
DE			
ME			
NE			

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Rice
AAFCO #: No official definition
IFN #: 4-03-932

Proximate Components, %	**x̄**	**n**	**SD**
Dry matter	87.78	6	2.20
Crude protein	7.87	9	1.04
Crude fiber	0.52	5	0.25
Ether extract	1.30	4	0.47
Acid ether extract	1.71	2	0.57
Ash	0.81	6	0.52
Carbohydrate Components, %			
Lactose	0.00	4	0.00
Sucrose	0.19	5	0.42
Raffinose	0.00	4	0.00
Stachyose	0.00	4	0.00
Verbascose	0.00	4	0.00
Oligosaccharides			
Starch	75.19	5	3.60
Neutral detergent fiber	1.28	4	0.95
Acid detergent fiber	0.64	3	0.14
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	**Total**			**Digestibility**					
				AID			**SID**		
	x̄	**n**	**SD**	**x̄**	**n**	**SD**	**x̄**	**n**	**SD**
Essential									
CP	7.87	9	1.04	80	2	5.66	94	1	
Arg	0.44	3	0.05	88	3	1.00	93	3	1.15
His	0.33	3	0.17	80	3	4.51	85	3	2.65
Ile	0.32	3	0.03	73	3	11.68	81	3	11.24
Leu	0.56	3	0.06	77	3	6.56	83	3	6.03
Lys	0.35	3	0.12	80	3	3.00	89	3	3.79
Met	0.25	3	0.19	85	2	9.19	87	2	9.90
Phe	0.44	3	0.01	75	3	3.61	80	3	3.06
Thr	0.23	3	0.04	72	3	2.52	85	3	6.66
Trp	0.11			63			77		
Val	0.42	3	0.04	73	3	5.20	86	3	3.21
Nonessential									
Ala	0.34	3	0.05	72	3	6.03	74	3	6.03
Asp	0.59	3	0.09	77	3	5.69	88	3	7.00
Cys	0.18			63			77		
Glu	1.12	3	0.09	82	3	5.29	89	3	5.86
Gly	0.31	3	0.05	73	3	4.73	77		
Pro	0.15	3	0.21	73	2	4.24	86		
Ser	0.28	3	0.06	74	3	7.21	92	3	10.00
Tyr	0.18	3	0.03	67	3	5.51	84		

Minerals	**x̄**	**n**	**SD**
Macro, %			
Ca	0.09	1	
Cl			
K			
Mg			
Na			
P	0.34	2	0.19
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %	0.18	1	
ATTD of P, %	29	1	
STTD of P, %	33	1	

Vitamins, mg/kg (unless otherwise noted)	**x̄**	**n**	**SD**
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			
Energy, kcal/kg			
GE	3723	4	49
DE	3681		
ME	3627		
NE	2881		

Fatty Acids, % of Ether Extract	**x̄**	**n**	**SD**
E.E.	2.78		
C-12:0	0.11		
C-14:0	0.36		
C-16:0	17.09		
C-16:1	0.36		
C-18:0	1.80		
C-18:1	35.90		
C-18:2	34.32		
C-18:3	1.51		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	19.35		
MUFA	36.26		
PUFA	35.83		
IV	98.86		
IVP	27.48		

TABLE 17-1 Continued

Ingredient: Rice Bran
AAFCO #: 75.7, AAFCO 2010, p. 388
IFN #: 4-03-928

Proximate Components, %	x̄	n	SD
Dry matter	91.60	3	1.5
Crude protein	15.11	3	1.28
Crude fiber			
Ether extract	13.77		
Acid ether extract			
Ash	14.80	3	4.82
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	27.00		
Neutral detergent fiber	26.28	3	4.05
Acid detergent fiber	11.87		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	15.11	3	1.28	57					
Arg	1.24	3	0.08	85			89		
His	0.42	3	0.03	78			87		
Ile	0.51	3	0.03	64			69		
Leu	1.04	3	0.07	65			70		
Lys	0.67	3	0.03	72			78		
Met	0.30	3	0.02	74			77		
Phe	0.65	3	0.05	68			73		
Thr	0.56	3	0.04	61			71		
Trp	0.19	3	0.01	64			73		
Val	0.78	3	0.04	66			69		
Nonessential									
Ala	0.89	3	0.05	61			66		
Asp	1.23	3	0.09	58			64		
Cys	0.27	3	0.02	66			68		
Glu	1.95	3	0.22	66			71		
Gly	0.81	3	0.05	48			59		
Pro	0.69	3	0.06	51			67		
Ser	0.69	3	0.05	60			69		
Tyr	0.40			77			81		

Minerals	x̄	n	SD
Macro, %			
Ca	0.22	3	0.05
Cl	0.07		
K	1.56		
Mg	0.90		
Na	0.03		
P	2.16	4	0.32
S	0.18		
Micro, ppm			
Cr			
Cu	9.00		
Fe	190		
I			
Mn	228		
Se	0.40		
Zn	30.00		
Phytate P, %	1.74	3	0.32
ATTD of P, %	13	4	1.24
STTD of P, %	23	4	1.41

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	9.7		
Water Soluble			
Vitamin B_6	26.0		
Vitamin B_{12}, μg/kg	0		
Biotin	0.35		
Folacin	2.20		
Niacin	293		
Pantothenic acid	23.0		
Riboflavin	2.5		
Thiamin	22.5		
Choline	1135		
Energy, kcal/kg			
GE	4772	3	299
DE	3100		
ME	2997		
NE	2281		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	20.85		
C-12:0	0.09		
C-14:0	0.37		
C-16:0	17.06		
C-16:1	0.36		
C-18:0	1.79		
C-18:1	35.85		
C-18:2	34.26		
C-18:3	1.52		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	19.31		
MUFA	36.21		
PUFA	35.77		
IV	98.72		
IVP	205.83		

TABLE 17-1 Continued

Ingredient: Rice Bran, Defatted
AAFCO #: 75.3, AAFCO 2010, p. 388
IFN #: 4-03-930

Proximate Components, %	x̄	n	SD
Dry matter	91.35	2	1.06
Crude protein	17.30	2	2.45
Crude fiber			
Ether extract	3.52	2	0.28
Acid ether extract			
Ash	11.51	1	
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	26.25	1	
Neutral detergent fiber	23.56	1	
Acid detergent fiber	1.31		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber	25.79	1	
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total x̄	Total n	Total SD	AID x̄	AID n	AID SD	SID x̄	SID n	SID SD
Essential									
CP	17.30	2	2.45						
Arg	1.57	1					83		
His	0.55	1					75		
Ile	0.62	1					75		
Leu	1.25	1					75		
Lys	0.80	1					70		
Met	0.36	1					78		
Phe	0.78	1					74		
Thr	0.68	1					69		
Trp	0.25	1					76		
Val	0.94	1					73		
Nonessential									
Ala	1.11	1							
Asp	1.59	1							
Cys	0.36	1					63		
Glu	2.55	1							
Gly	0.99	1							
Pro	0.81	1							
Ser	0.84	1							
Tyr	0.31						86		

Minerals	x̄	n	SD
Macro, %			
Ca	0.1		
Cl			
K			
Mg			
Na			
P	1.89		
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %			
STTD of P, %	28		

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			
Energy, kcal/kg			
GE	4056	1	
DE	2199		
ME	2081		
NE	1553		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Rice, Broken
AAFCO #: 75.4, AAFCO 2010, p. 388
IFN #: 4-03-932

Proximate Components, %	x̄	n	SD
Dry matter	89.00		
Crude protein	7.90		
Crude fiber			
Ether extract	1.30		
Acid ether extract			
Ash			
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	75.19		
Neutral detergent fiber	12.20		
Acid detergent fiber	6.40		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	7.90								
Arg	0.52						89		
His	0.18						84		
Ile	0.34						81		
Leu	0.67						83		
Lys	0.30						77		
Met	0.18						85		
Phe	0.39						84		
Thr	0.26						76		
Trp	0.10						77		
Val	0.49						78		
Nonessential									
Ala									
Asp									
Cys	0.11						73		
Glu									
Gly									
Pro									
Ser									
Tyr	0.38						86		

Minerals	x̄	n	SD
Macro, %			
Ca	0.04		
Cl	0.07		
K	0.13		
Mg	0.11		
Na	0.04		
P	0.21	2	0.06
S	0.06		
Micro, ppm			
Cr			
Cu	21		
Fe	18		
I			
Mn	12		
Se	0.27		
Zn	17		
Phytate P, %	0.14	1	
ATTD of P, %	31	2	1.34
STTD of P, %	38	2	2.76

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	2.00		
Water Soluble			
Vitamin B_6	28.00		
Vitamin B_{12}, μg/kg	0.00		
Biotin	0.08		
Folacin	0.20		
Niacin	25		
Pantothenic acid	3.30		
Riboflavin	0.40		
Thiamin	1.40		
Choline	1003		
Energy, kcal/kg			
GE	4290		
DE	3565		
ME	3511		
NE	2778		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	1.20		
C-12:0	0.09		
C-14:0	0.63		
C-16:0	16.29		
C-16:1	0.27		
C-18:0	1.71		
C-18:1	36.18		
C-18:2	32.31		
C-18:3	1.35		
C-18:4	0.00		
C-20:0	0.18		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	18.90		
MUFA	36.45		
PUFA	33.66		
IV	94.95		
IVP	11.39		

TABLE 17-1 Continued

Ingredient: Rice, Polished
AAFCO #: No official definition
IFN #: 4-03-932

Proximate Components, %	x̄	n	SD
Dry matter	87.90	1	
Crude protein	8.00	1	
Crude fiber			
Ether extract	1.41	1	
Acid ether extract			
Ash			
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	83.59	1	
Neutral detergent fiber	12.2		
Acid detergent fiber	3.10		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber	1.32	1	
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	8.00	1							
Arg	0.52								
His	0.18								
Ile	0.34								
Leu	0.67								
Lys	0.30								
Met	0.18								
Phe	0.39								
Thr	0.26								
Trp	0.10								
Val	0.49								
Nonessential									
Ala									
Asp									
Cys	0.11								
Glu									
Gly									
Pro									
Ser									
Tyr	0.38								

Minerals	x̄	n	SD
Macro, %			
Ca	0.04		
Cl	0.07		
K	0.13		
Mg	0.11		
Na	0.04		
P	0.18		
S	0.06		
Micro, ppm			
Cr			
Cu	21		
Fe	18		
I			
Mn	12		
Se	0.27		
Zn	17		
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	2.0		
Water Soluble			
Vitamin B_6	28.0		
Vitamin B_{12}, μg/kg	0		
Biotin	0.08		
Folacin	0.20		
Niacin	25		
Pantothenic acid	3.3		
Riboflavin	0.4		
Thiamin	1.4		
Choline	1003		

Energy, kcal/kg			
GE	4298		
DE	3565		
ME	3511		
NE	2847		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	1.42		
C-12:0	0.00		
C-14:0	0.56		
C-16:0	24.30		
C-16:1	0.35		
C-18:0	1.83		
C-18:1	30.70		
C-18:2	22.04		
C-18:3	4.72		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	26.69		
MUFA	31.06		
PUFA	26.76		
IV	80.74		
IVP	11.46		

TABLE 17-1 Continued

Ingredient: Rice Protein Concentrate
Rice gluten, a co-product from production of rice starch, manufacturing process is comparable to the production of quality wheat gluten.
AAFCO #: No official definition

Proximate Components, %	x̄	n	SD
Dry matter	92.68	1	
Crude protein	67.51	1	
Crude fiber			
Ether extract	0.00		
Acid ether extract			
Ash	3.41	1	

Carbohydrate Components, %	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	0.00		
Neutral detergent fiber			
Acid detergent fiber	0.00		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total x̄	Total n	Total SD	AID x̄	AID n	AID SD	SID x̄	SID n	SID SD
Essential									
CP	67.51	1							
Arg	5.26	1							
His	1.65	1							
Ile	2.91	1							
Leu	5.31	1							
Lys	2.21	1							
Met	1.77	1							
Phe	3.52	1							
Thr	2.12	1							
Trp	0.81	1							
Val	4.13	1							
Nonessential									
Ala	3.47	1							
Asp	5.39	1							
Cys	1.45	1							
Glu	10.87	1							
Gly	2.77	1							
Pro	2.94	1							
Ser	2.36	1							
Tyr	3.32	1							

Minerals	x̄	n	SD
Macro, %			
Ca	0.10	1	
Cl			
K			
Mg			
Na			
P	0.75	1	
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg	x̄	n	SD
GE	4954	1	
DE	4724	1	
ME	4265		
NE	2692		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Rye
AAFCO #: No official definition
IFN #: 4-04-047

Proximate Components, %	x̄	n	SD
Dry matter	89.40	1	
Crude protein	11.66	3	2.67
Crude fiber	2.71	2	1.12
Ether extract	1.98	2	0.74
Acid ether extract			
Ash	1.78	1	
Carbohydrate Components, %			
Lactose	0.00	1	0.00
Sucrose	0.00	1	0.00
Raffinose	0.00	1	0.00
Stachyose	0.00	1	0.00
Verbascose	0.00	1	0.00
Oligosaccharides			
Starch	59.34	2	1.36
Neutral detergent fiber	12.26	1	
Acid detergent fiber	4.60		
Hemicellulose			
Acid detergent lignin	0.77	1	
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility AID			Digestibility SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	11.66	3	2.67	69	4	6.87	83	4	9.58
Arg	0.70	2	0.27	73			79		
His	0.25	2	0.08	71			79		
Ile	0.34	2	0.07	68			78		
Leu	0.70	2	0.26	71			79		
Lys	0.43	2	0.10	64			74		
Met	0.16	2	0.00	76			81		
Phe	0.50	2	0.16	76			82		
Thr	0.37	2	0.12	59			74		
Trp	0.10	1		67			76		
Val	0.49	2	0.13	67			77		
Nonessential									
Ala	0.44	2	0.05	60			70		
Asp	0.77	2	0.13	68			79		
Cys	0.19	2	0.01	74			83		
Glu	2.63	2	0.74	89	2	0.21	93	2	0.25
Gly	0.48	2	0.11	60			79		
Pro	1.57	1		86	1		98		
Ser	0.44	2	0.08	73			84		
Tyr	0.25	2	0.10	65			76		

Minerals	x̄	n	SD
Macro, %			
Ca	0.08		
Cl	0.03		
K	0.48		
Mg	0.12		
Na	0.02		
P	0.30		
S	0.15		
Micro, ppm			
Cr			
Cu	7		
Fe	60		
I			
Mn	58		
Se	0.38		
Zn	31		
Phytate P, %	0.2		
ATTD of P, %	43		
STTD of P, %	50		

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	9.0		
Water Soluble			
Vitamin B_6	2.6		
Vitamin B_{12}, μg/kg	0		
Biotin	0.08		
Folacin	0.60		
Niacin	19		
Pantothenic acid	8.0		
Riboflavin	1.6		
Thiamin	3.6		
Choline	419		
Energy, kcal/kg			
GE	4350		
DE	3270		
ME	3191		
NE	2460		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	2.50		
C-12:0	0.00		
C-14:0	0.12		
C-16:0	10.84		
C-16:1	0.40		
C-18:0	0.36		
C-18:1	11.20		
C-18:2	38.32		
C-18:3	6.28		
C-18:4			
C-20:0	0.00		
C-20:1	0.52		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	11.32		
MUFA	12.12		
PUFA	44.60		
IV	97.42		
IVP	24.35		

TABLE 17-1 Continued

Ingredient: Safflower Meal
AAFCO #: 71.131, AAFCO 2010, p. 386
IFN #: 5-04-110

Proximate Components, %	x̄	n	SD
Dry matter	92.00		
Crude protein	23.40		
Crude fiber			
Ether extract	2.24		
Acid ether extract			
Ash			
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	0.90		
Neutral detergent fiber	55.9		
Acid detergent fiber	36.56		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	23.4								
Arg	2.04						84		
His	0.59						84		
Ile	0.67						87		
Leu	1.52						87		
Lys	0.74						82		
Met	0.34						84		
Phe	1.07						90		
Thr	0.65						79		
Trp	0.33						84		
Val	1.18						88		
Nonessential									
Ala									
Asp									
Cys	0.38						84		
Glu									
Gly									
Pro									
Ser									
Tyr	0.77								

Minerals	x̄	n	SD
Macro, %			
Ca	0.34		
Cl	0.08		
K	0.76		
Mg	0.35		
Na	0.05		
P	0.75		
S	0.13		
Micro, ppm			
Cr			
Cu	10		
Fe	495		
I			
Mn	18		
Se			
Zn	41		
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	16.0		
Water Soluble			
Vitamin B_6	12.0		
Vitamin B_{12}, μg/kg	0		
Biotin	1.03		
Folacin	0.50		
Niacin	11		
Pantothenic acid	33.9		
Riboflavin	3.3		
Thiamin	4.6		
Choline	820		

Energy, kcal/kg	x̄	n	SD
GE	4589		
DE	2840		
ME	2681		
NE	1497		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	2.39		
C-12:0	0.00		
C-14:0	0.08		
C-16:0	6.03		
C-16:1	0.08		
C-18:0	2.18		
C-18:1	11.30		
C-18:2	65.94		
C-18:3	0.25		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	8.28		
MUFA	11.38		
PUFA	66.19		
IV	130.27		
IVP	31.13		

TABLE 17-1 Continued

Ingredient: Safflower Meal, Dehulled
AAFCO #: No official definition
IFN #: 5-07-959

Proximate Components, %	x̄	n	SD	Amino Acids, % Total	x̄	n	SD	Digestibility AID x̄	AID n	AID SD	SID x̄	SID n	SID SD
Dry matter	92.00			Essential									
Crude protein	42.50			CP	42.50								
Crude fiber				Arg	3.59								
Ether extract	1.30			His	1.07								
Acid ether extract				Ile	1.69								
Ash				Leu	2.57								
Carbohydrate Components, %				Lys	1.17								
				Met	0.66								
Lactose				Phe	2.00								
Sucrose				Thr	1.28								
Raffinose				Trp	0.54								
Stachyose				Val	2.33								
Verbascose				Nonessential									
Oligosaccharides				Ala									
Starch	1.40			Asp									
Neutral detergent fiber	25.9			Cys	0.69								
Acid detergent fiber	18.0			Glu									
Hemicellulose				Gly									
Acid detergent lignin				Pro									
Total dietary fiber				Ser									
Insoluble dietary fiber				Tyr	1.08								
Soluble dietary fiber													

Minerals	x̄	n	SD	Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD	Fatty Acids, % of Ether Extract	x̄	n	SD
Macro, %				Fat Soluble				E.E.			
Ca	0.37			β-Carotene				C-12:0			
Cl	0.16			Vitamin E	16.0			C-14:0			
K	1.00			Water Soluble				C-16:0			
Mg	1.02			Vitamin B_6	11.3			C-16:1			
Na	0.04			Vitamin B_{12}, μg/kg	0			C-18:0			
P	1.31			Biotin	1.03			C-18:1			
S	0.20			Folacin	1.60			C-18:2			
Micro, ppm				Niacin	22			C-18:3			
Cr				Pantothenic acid	39.1			C-18:4			
Cu	9			Riboflavin	2.4			C-20:0			
Fe	484			Thiamin	4.5			C-20:1			
I				Choline	3248			C-20:4			
Mn	39							C-20:5			
Se								C-22:0			
Zn	33			**Energy, kcal/kg**				C-22:1			
								C-22:5			
Phytate P, %				GE	4823			C-22:6			
ATTD of P, %				DE	3055			C-24:0			
STTD of P, %				ME	2766			SFA			
				NE	1623			MUFA			
								PUFA			
								IV			
								IVP			

TABLE 17-1 Continued

Ingredient: Salmon Protein Hydrolysate
AAFCO #: 51.11, AAFCO 2010, p. 359
IFN #: 5-18-778

Proximate Components, %	x̄	n	SD
Dry matter	91.99	2	0.78
Crude protein	90.79	2	2.69
Crude fiber			
Ether extract	2.12	1	
Acid ether extract			
Ash	4.77	2	2.93

Carbohydrate Components, %	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber			
Acid detergent fiber			
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	90.79	2	2.69						
Arg	5.33	2	0.19						
His	1.55	2	0.05						
Ile	2.11	2	0.06						
Leu	3.97	2	0						
Lys	4.96	2	0.12						
Met	1.84	2	0.06						
Phe	2.08	2	0.02						
Thr	2.68	2	0.08						
Trp	0.44	2	0.06						
Val	2.69	2	0.12						
Nonessential									
Ala	5.77	2	0.22						
Asp	6.05	2	0.18						
Cys	0.41	2	0.01						
Glu	9.82	2	0.26						
Gly	11.18	2	1.14						
Pro	5.74	2	0.61						
Ser	2.85	2	0.35						
Tyr	1.34	2	0.03						

Minerals	x̄	n	SD
Macro, %			
Ca	0.09	2	0.05
Cl			
K	1.79	1	
Mg	0.07	1	
Na			
P	0.84	2	0.27
S			
Micro, ppm			
Cr			
Cu			
Fe	6.29	1	
I			
Mn			
Se			
Zn	54.13	1	
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg	x̄	n	SD
GE	4713	2	135
DE	4173	1	
ME	3556		
NE	2129		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Sesame Meal
AAFCO #: No official definition
IFN #: 5-04-220

Proximate Components, %

	x̄	n	SD
Dry matter	93.00		
Crude protein	42.60		
Crude fiber			
Ether extract	7.50		
Acid ether extract			
Ash			

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	1.80		
Neutral detergent fiber	18.00		
Acid detergent fiber	13.20		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total x̄	Total n	Total SD	AID x̄	AID n	AID SD	SID x̄	SID n	SID SD
Essential									
CP	42.60			81					
Arg	4.86			94			96		
His	0.98			76			84		
Ile	1.47			85			87		
Leu	2.74			85			92		
Lys	1.01			76			85		
Met	1.15			90			92		
Phe	1.77			89			93		
Thr	1.44			78			90		
Trp	0.54			85			85		
Val	1.87			84			89		
Nonessential									
Ala	1.62			82			84		
Asp	2.30			82			84		
Cys	0.82			86			92		
Glu	6.53			83			84		
Gly	1.65			80			84		
Pro	1.23			78			84		
Ser	1.50			81			84		
Tyr	1.52			87			91		

Minerals

	x̄	n	SD
Macro, %			
Ca	1.70		
Cl	0.07		
K	1.10		
Mg	0.54		
Na	0.04		
P	1.18		
S	0.56		
Micro, ppm			
Cr			
Cu	34		
Fe	93		
I			
Mn	53		
Se	0.21		
Zn	100		
Phytate P, %	0.89		
ATTD of P, %	29		
STTD of P, %	42		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene	0.2		
Vitamin E	1.0		
Water Soluble			
Vitamin B_6	12.5		
Vitamin B_{12}, μg/kg	0		
Biotin	0.24		
Folacin			
Niacin	30		
Pantothenic acid	6.0		
Riboflavin	3.6		
Thiamin	2.8		
Choline	1536		

Energy, kcal/kg

GE	4702		
DE	3350		
ME	3060		
NE	1972		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0	0.00		
C-14:0	0.25		
C-16:0	8.94		
C-16:1	0.30		
C-18:0	4.21		
C-18:1	37.29		
C-18:2	43.03		
C-18:3	0.76		
C-18:4			
C-20:0	0.00		
C-20:1	0.14		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	13.40		
MUFA	37.73		
PUFA	43.79		
IV	113.86		
IVP	85.40		

TABLE 17-1 Continued

Ingredient: Sorghum
AAFCO #: 42.1, AAFCO 2010, p. 354
IFN #: 4-04-379

Proximate Components, %	x̄	n	SD
Dry matter	89.39	26	2.63
Crude protein	9.36	29	1.10
Crude fiber	2.14	4	0.16
Ether extract	3.42	6	0.43
Acid ether extract	2.12	3	1.18
Ash	1.64	17	0.34
Carbohydrate Components, %			
Lactose	0.00	4	0.00
Sucrose	0.00	4	0.00
Raffinose	0.00	4	0.00
Stachyose	0.00	4	0.00
Verbascose	0.00	4	0.00
Oligosaccharides			
Starch	70.05	5	8.71
Neutral detergent fiber	10.63	16	3.28
Acid detergent fiber	4.93	16	1.48
Hemicellulose			
Acid detergent lignin	0.44	1	
Total dietary fiber	4.35	1	
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility AID			Digestibility SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	9.36	29	1.10	63	16	6.96	77	16	7.29
Arg	0.36	22	0.05	68	16	10.02	80	16	10.39
His	0.21	21	0.03	64	15	8.32	74	15	8.19
Ile	0.36	22	0.05	69	16	6.19	78	16	6.15
Leu	1.21	22	0.15	78	16	4.77	83	16	5.06
Lys	0.20	22	0.05	53	16	11.87	74	16	12.44
Met	0.16	20	0.03	74	16	6.99	79	16	7.16
Phe	0.48	19	0.06	76	15	5.51	83	15	6.14
Thr	0.30	22	0.04	54	16	9.35	75	16	8.48
Trp	0.07	18	0.02	65	14	8.88	74	2	24.75
Val	0.46	22	0.06	66	16	7.08	77	16	7.38
Nonessential									
Ala	0.84	20	0.10	73	16	5.02	79	16	5.07
Asp	0.60	20	0.10	66	16	6.43	79	16	7.08
Cys	0.18	20	0.02	56	16	9.26	67	16	9.06
Glu	1.84	20	0.27	74	16	15.45	81	16	8.70
Gly	0.31	20	0.04	34	16	17.67	67	16	19.01
Pro	0.74	19	0.10	46	15	22.86	74	15	29.54
Ser	0.39	20	0.05	66	16	6.02	81	16	6.23
Tyr	0.32	19	0.05	69	15	6.56	75	15	7.71

Minerals	x̄	n	SD
Macro, %			
Ca	0.02	9	0.01
Cl	0.09		
K	0.35		
Mg	0.15		
Na	0.01		
P	0.27	10	0.06
S	0.08		
Micro, ppm			
Cr			
Cu	5.00		
Fe	45		
I			
Mn	15.00		
Se	0.20		
Zn	15.00		
Phytate P, %	0.18	2	0.05
ATTD of P, %	30	4	7.24
STTD of P, %	40	4	7.33

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	5.0		
Water Soluble			
Vitamin B_6	5.2		
Vitamin B_{12}, μg/kg	0		
Biotin	0.26		
Folacin	0.17		
Niacin	41		
Pantothenic acid	12.4		
Riboflavin	1.3		
Thiamin	3.0		
Choline	668		
Energy, kcal/kg			
GE	3881	4	49
DE	3596	3	17
ME	3532		
NE	2780		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	3.30		
C-12:0	0.21		
C-14:0	0.27		
C-16:0	12.33		
C-16:1	0.88		
C-18:0	1.06		
C-18:1	29.21		
C-18:2	39.55		
C-18:3	1.97		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	13.88		
MUFA	30.09		
PUFA	41.52		
IV	104.08		
IVP	34.35		

TABLE 17-1 Continued

Ingredient: Sorghum, DDGS
AAFCO #: 27.6, AAFCO 2010, p. 343
IFN #: 5-04-375

Proximate Components, %	x̄	n	SD
Dry matter	89.84	4	1.69
Crude protein	30.80	4	1.34
Crude fiber	7.06	2	0.22
Ether extract	9.75	4	1.69
Acid ether extract			
Ash	6.62	3	4.57
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	0.00		
Neutral detergent fiber	33.60	4	6.17
Acid detergent fiber	22.68	4	3.44
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	30.80	4	1.34	65	1		73	1	
Arg	1.10	1		70	1		79	1	
His	0.71	1		69	1		72	1	
Ile	1.29	3	0.06	72	1		74	1	
Leu	4.01	3	0.14	76	1		77	1	
Lys	0.82	3	0.14	59	1		64	1	
Met	0.54	3	0.04	75	1		77	1	
Phe	1.68	1		74	1		77	1	
Thr	1.06	3	0.03	64	1		70	1	
Trp	0.25	3	0.09	67	1		72	1	
Val	1.65	3	0.03	71	1		74	1	
Nonessential									
Ala	2.90	1		72	1		75	1	
Asp	2.17	1		65	1		69	1	
Cys	0.53	3	0.05	63	1		67	1	
Glu	6.31	1		75	1		77	1	
Gly	1.03	1		41	1		69	1	
Pro	2.50	1		35	1		74	1	
Ser	1.40	1		68	1		78	1	
Tyr									

Minerals	x̄	n	SD
Macro, %			
Ca	0.12	1	
Cl			
K			
Mg			
Na			
P	0.76	1	
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg			
GE	4860		
DE	3878		
ME	3669		
NE	2394		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Soybean Hulls
AAFCO #: 84.3, AAFCO 2010, p. 390
IFN #: 1-04-560

Proximate Components, %	x̄	n	SD
Dry matter	90.59	4	1.23
Crude protein	10.27	7	1.45
Crude fiber	35.75	2	5.15
Ether extract	1.29	2	0.71
Acid ether extract	1.71	1	
Ash	4.46	4	0.31
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	3.65		
Neutral detergent fiber	59.39	7	4.7
Acid detergent fiber	41.55	6	1.93
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	10.27	7	1.45	44					
Arg	0.60	1		74			82		
His	0.29	1		47			56		
Ile	0.38	2	0.09	56			67		
Leu	0.76	1		59			68		
Lys	0.66	2	0.08	51			58		
Met	0.14	2	0.04	60			70		
Phe	0.46	1		62			71		
Thr	0.39	2	0.09	47			62		
Trp	0.09	2	0.01	49			62		
Val	0.51	2	0.09	50			61		
Nonessential									
Ala	0.48	1		44			54		
Asp	1.20	1		47			54		
Cys	0.20	2	0.05	51			63		
Glu	1.30	1		45			54		
Gly	0.82	1		43			54		
Pro	0.47	1		34			54		
Ser	0.62	1		43			54		
Tyr	0.51	1		56			63		

Minerals	x̄	n	SD
Macro, %			
Ca	0.54	2	0.07
Cl			
K			
Mg			
Na			
P	0.12	2	0.04
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %	0.08		
ATTD of P, %	20		
STTD of P, %	33		

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			
Energy, kcal/kg			
GE	4210	1	
DE	2008		
ME	1938		
NE	989		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	2.20		
C-12:0	0.00		
C-14:0	0.10		
C-16:0	9.98		
C-16:1	0.19		
C-18:0	3.61		
C-18:1	20.62		
C-18:2	50.45		
C-18:3	7.03		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	13.68		
MUFA	20.81		
PUFA	57.48		
IV	129.24		
IVP	28.43		

TABLE 17-1 Continued

Ingredient: Soybean Meal, Dehulled, Expelled
AAFCO #: 84.71, AAFCO 2010, p. 392

Proximate Components, %

	x̄	n	SD
Dry matter	95.57	4	1.56
Crude protein	45.13	4	3.60
Crude fiber	3.30	1	
Ether extract	6.64	2	1.10
Acid ether extract			
Ash	6.24	1	

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	1.89		
Neutral detergent fiber			
Acid detergent fiber	6.33		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility AID			Digestibility SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	45.13	4	3.60	81	3	4.20	89	3	0.55
Arg	3.02	4	0.4	90	3	3.07	95	3	0.39
His	1.14	4	0.15	86	3	3.39	90	3	1.49
Ile	1.90	4	0.33	85	3	3.94	89	3	1.81
Leu	3.21	4	0.51	85	3	3.35	88	3	1.77
Lys	2.79	4	0.22	86	3	4.05	90	3	2.45
Met	0.60	4	0.07	80	3	7.82	85	3	4.84
Phe	2.15	4	0.31	86	3	3.52	89	3	2.51
Thr	1.73	4	0.14	76	3	3.62	84	3	1.82
Trp	0.69	2	0.04	87	1		89	1	
Val	2.01	4	0.36	83	3	4.00	88	3	1.49
Nonessential									
Ala	1.88	3	0.29	81	3	3.59	88	3	0.62
Asp	4.73	3	0.75	85	3	4.16	88	3	2.62
Cys	0.72	3	0.1	79	3	3.48	87	3	1.84
Glu	7.35	3	1.19	88	3	3.83	91	3	2.33
Gly	1.82	3	0.22	72	3	4.17	91	3	6.31
Pro	2.16	3	0.25	70	3	11.60	131	3	23.54
Ser	2.11	3	0.07	82	3	2.75	88	3	1.10
Tyr	1.47	3	0.27	84	3	2.63	87	3	1.26

Minerals

	x̄	n	SD
Macro, %			
Ca			
Cl			
K			
Mg			
Na			
P			
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	4710	1	
DE	4210	1	
ME	3903		
NE	2598		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	1.90		
C-12:0	0.00		
C-14:0	0.08		
C-16:0	7.88		
C-16:1	0.15		
C-18:0	2.85		
C-18:1	16.28		
C-18:2	39.83		
C-18:3	5.55		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	10.80		
MUFA	16.43		
PUFA	45.38		
IV	102.03		
IVP	19.39		

TABLE 17-1 Continued

Ingredient: Soybean Meal, Dehulled, Solvent Extracted
AAFCO #: 84.7, AAFCO 2010, p. 391
IFN #: 5-04-612

Proximate Components, %

	x̄	n	SD
Dry matter	89.98	101	2.62
Crude protein	47.73	154	2.30
Crude fiber	3.89	38	1.60
Ether extract	1.52	70	0.91
Acid ether extract	2.86	6	0.96
Ash	6.27	56	0.51

Carbohydrate Components, %

	x̄	n	SD
Lactose	0.00	7	0.00
Sucrose	4.30	19	3.60
Raffinose	3.78	19	14.25
Stachyose	7.33	19	19.54
Verbascose	0.00	7	0.00
Oligosaccharides	3.81	3	0.16
Starch	1.89		
Neutral detergent fiber	8.21	32	2.90
Acid detergent fiber	5.28	30	2.43
Hemicellulose	3.90	6	0.48
Acid detergent lignin	1.10	1	
Total dietary fiber	16.71	8	3.47
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility AID			Digestibility SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	47.73	154	2.30	82	69	5.03	87	68	4.48
Arg	3.45	107	0.26	92	83	3.22	94	83	3.12
His	1.28	104	0.10	87	82	4.30	90	82	4.15
Ile	2.14	113	0.18	87	83	3.96	89	82	3.79
Leu	3.62	107	0.27	86	83	3.58	88	83	3.45
Lys	2.96	118	0.19	87	83	3.38	89	83	3.44
Met	0.66	112	0.08	88	77	4.82	90	77	4.70
Phe	2.40	105	0.19	86	82	3.85	88	82	3.65
Thr	1.86	117	0.11	80	83	4.59	85	83	4.47
Trp	0.66	87	0.08	88	59	4.23	91	59	3.32
Val	2.23	115	0.19	83	83	4.53	87	83	4.16
Nonessential									
Ala	2.06	80	0.16	80	61	5.37	85	61	5.94
Asp	5.41	81	0.46	85	60	3.61	87	60	3.42
Cys	0.70	98	0.08	79	74	4.64	84	74	4.55
Glu	8.54	80	1.19	87	61	4.01	89	61	4.24
Gly	1.99	78	0.20	75	61	7.41	84	61	6.38
Pro	2.53	63	0.41	79	51	10.99	113	51	85.14
Ser	2.36	81	0.23	84	61	4.64	89	61	5.62
Tyr	1.59	86	0.20	84	59	5.15	88	56	4.70

Minerals

	x̄	n	SD
Macro, %			
Ca	0.33	65	0.10
Cl	0.49	9	0.12
K	2.24	15	0.12
Mg	0.27	13	0.01
Na	0.08	5	0.05
P	0.71	73	0.09
S	0.40	10	0.04
Micro, ppm			
Cr			
Cu	15.13	15	1.30
Fe	98.19	11	42.43
I			
Mn	35.49	14	5.56
Se	0.27		
Zn	48.81	15	9.39
Phytate P, %	0.38	20	0.07
ATTD of P, %	39	20	6.24
STTD of P, %	48	20	7.62

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene	0.2		
Vitamin E	0.07	3	0.01
Water Soluble			
Vitamin B_6	6.4		
Vitamin B_{12}, μg/kg	0		
Biotin	0.26		
Folacin	1.37		
Niacin	22		
Pantothenic acid	15.0		
Riboflavin	3.1		
Thiamin	3.2		
Choline	2731		

Energy, kcal/kg

	x̄	n	SD
GE	4256	42	192
DE	3619	3	184
ME	3294		
NE	2087		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	1.50		
C-12:0	0.00		
C-14:0	0.08		
C-16:0	7.88		
C-16:1	0.15		
C-18:0	2.85		
C-18:1	16.28		
C-18:2	39.83		
C-18:3	5.55		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	10.80		
MUFA	16.43		
PUFA	45.38		
IV	102.03		
IVP	15.30		

TABLE 17-1 Continued

Ingredient: Soybean Meal, Enzyme Treated
AAFCO #: 84.63, AAFCO 2010, p. 392

Proximate Components, %

	x̄	n	SD
Dry matter	92.70	4	0.84
Crude protein	55.62	4	2.11
Crude fiber	4.06	4	0.94
Ether extract	1.82	4	0.48
Acid ether extract			
Ash	7.05	3	0.06

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber			
Acid detergent fiber			
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility AID			Digestibility SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	55.62	4	2.11	82	4	3.95	88	4	2.94
Arg	3.95	4	0.19	92	5	1.81	96	5	2.94
His	1.41	4	0.06	87	5	3.13	90	5	4.71
Ile	2.48	4	0.15	86	5	3.17	89	5	3.65
Leu	4.09	4	0.19	86	5	3.75	89	5	4.42
Lys	3.20	4	0.13	83	5	3.30	86	5	3.78
Met	0.71	4	0.03	88	4	2.10	91	4	1.89
Phe	2.78	4	0.15	83	5	6.07	86	5	7.81
Thr	2.13	4	0.13	78	5	5.24	83	5	5.93
Trp	0.72	4	0.04	80	4	3.32	83	4	4.41
Val	2.57	4	0.17	84	5	5.06	89	5	5.33
Nonessential									
Ala	2.41	4	0.14	82	4	3.58	86	4	2.61
Asp	6.14	4	0.40	83	4	2.57	86	4	2.91
Cys	0.78	4	0.04	68	4	7.51	73	4	10.43
Glu	9.62	4	0.75	86	4	4.61	88	4	5.49
Gly	2.32	4	0.08	76	4	11.21	89	4	3.79
Pro	2.73	4	0.20	73	4	19.92	112	4	24.08
Ser	2.66	4	0.25	83	4	3.89	87	4	3.30
Tyr	2.03	1		86	1		92	1	

Minerals

	x̄	n	SD
Macro, %			
Ca	0.31	3	0.04
Cl			
K			
Mg			
Na			
P	0.75	3	0.02
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %	60	1	
STTD of P, %	66	1	

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	4451	3	20
DE	3914	2	37
ME	3536		
NE			

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Soybean Meal, Expelled
AAFCO #:84.6, AAFCO 2010, p. 391
IFN #: 5-04-600

Proximate Components, %

	x̄	n	SD
Dry matter	93.85	6	3.56
Crude protein	44.56	7	2.15
Crude fiber	5.60	2	1.13
Ether extract	5.69	5	1.3
Acid ether extract	9.87	2	0.51
Ash	5.70	3	0.28

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose	7.10	1	
Raffinose	0.77	1	
Stachyose	4.88	1	
Verbascose			
Oligosaccharides			
Starch	1.89		
Neutral detergent fiber	13.84	3	1.4
Acid detergent fiber	7.35	3	0.74
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility AID			Digestibility SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	44.56	7	2.15	84	2	3.39	89	2	0.38
Arg	3.13	6	0.46	93	2	0.78	96	2	0.82
His	1.17	6	0.12	88	2	1.63	91	2	0.29
Ile	1.97	6	0.29	88	2	1.91	91	2	0.62
Leu	3.29	6	0.39	88	2	0.64	89		
Lys	2.85	6	0.35	89	2	3.18	90		
Met	0.56	6	0.11	88	2	0.71	91	2	0.26
Phe	2.19	6	0.22	89	2	1.27	90		
Thr	1.73	6	0.07	79	2	0.49	85		
Trp	0.67	3	0.07	88	2	0.92	89		
Val	2.06	6	0.29	86	2	2.69	88		
Nonessential									
Ala	1.89	6	0.16	83	2	2.76	88	2	0.03
Asp	4.84	6	0.47	86	2	4.31	88	2	2.93
Cys	0.70	5	0.07	78	2	6.22	83		
Glu	7.56	6	0.77	88	2	5.80	90	2	4.66
Gly	1.89	6	0.18	71	2	3.54	84	2	3.64
Pro	2.16	5	0.18	81	2	1.56	111	2	12.57
Ser	2.11	6	0.05	85	2	0.14	89	2	1.92
Tyr	1.50	6	0.17	87	2	0.64	89	2	1.19

Minerals

	x̄	n	SD
Macro, %			
Ca	0.28	1	
Cl			
K			
Mg			
Na			
P	0.66	1	
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %	39		
STTD of P, %	48		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	4692	3	29
DE	3876	2	345
ME	3573		
NE	2344		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	1.90		
C-12:0	0.00		
C-14:0	0.08		
C-16:0	7.88		
C-16:1	0.15		
C-18:0	2.85		
C-18:1	16.28		
C-18:2	39.83		
C-18:3	5.55		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	10.80		
MUFA	16.43		
PUFA	45.38		
IV	102.03		
IVP	19.39		

TABLE 17-1 Continued

Ingredient: Soybean Meal, Fermented
AAFCO #: No official definition

Proximate Components, %

	x̄	n	SD
Dry matter	92.88	3	2.80
Crude protein	54.07	4	2.67
Crude fiber	3.46	2	0.21
Ether extract	2.30	2	2.12
Acid ether extract			
Ash	6.98	1	

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber			
Acid detergent fiber			
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	54.07	4	2.67	72	2	2.76	79	2	3.46
Arg	3.70	3	0.21	87	2	1.06	90	2	4.18
His	1.37	3	0.08	79	2	2.19	81	2	4.32
Ile	2.55	3	0.12	79	2	3.46	82	2	5.17
Leu	4.25	3	0.26	79	2	3.11	82	2	4.96
Lys	3.14	4	0.22	72	2	1.20	75	2	3.30
Met	0.75	4	0.04	85	2	1.63	88	2	0.42
Phe	2.87	3	0.22	77	2	7.42	80	2	9.82
Thr	2.09	4	0.10	68	2	2.12	73	2	7.01
Trp	0.69	4	0.04	75	2	5.73	78	2	7.71
Val	2.67	3	0.17	75	2	1.98	80	2	5.79
Nonessential									
Ala	2.45	3	0.14	74	2	1.48	79	2	2.35
Asp	5.98	2	0.44	75	2	3.11	78	2	5.17
Cys	0.77	3	0.02	58	2	4.60	64	2	8.57
Glu	9.12	2	0.80	76	2	7.00	78	2	8.43
Gly	2.34	3	0.12	60	2	13.86	75	2	1.78
Pro	2.74	3	0.27	63	2	10.04	109	2	31.33
Ser	2.51	3	0.25	75	2	0.92	80	2	2.95
Tyr	2.08	2	0.15	84	1		88	1	

Minerals

	x̄	n	SD
Macro, %			
Ca	0.29	2	0.00
Cl			
K			
Mg			
Na			
P	0.80	2	0.03
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %	60		
STTD of P, %	66	1	

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, µg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	4533	1	
DE	3975	1	
ME	3607		
NE			

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Soybean Meal, High Protein, Dehulled, Solvent Extracted
AAFCO #: 84.7, AAFCO 2010, p. 391
IFN #: 5-04-612

Proximate Components, %

	x̄	n	SD
Dry matter	88.66	2	0.77
Crude protein	51.17	3	3.88
Crude fiber	3.62	1	
Ether extract	1.10	2	1.13
Acid ether extract			
Ash	6.19	1	

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose	4.28	1	
Raffinose	0.68	1	
Stachyose	3.12	1	
Verbascose			
Oligosaccharides			
Starch	1.89		
Neutral detergent fiber	5.50	1	
Acid detergent fiber	2.95	1	
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	51.17	3	3.88	80	3	0.58	85	3	2.97
Arg	3.78	3	0.45	90	3	1.21	92	3	2.43
His	1.31	3	0.23	86	3	0.23	88	3	1.71
Ile	2.36	3	0.18	82	3	2.31	84	3	3.37
Leu	3.87	3	0.38	83	3	1.73	85	3	2.83
Lys	3.11	3	0.35	85	3	1.27	87	3	2.76
Met	0.68	3	0.09	87	3	0.87	89	3	0.06
Phe	2.59	3	0.22	82	3	3.29	84	3	4.27
Thr	1.92	3	0.15	76	3	1.42	81	3	4.09
Trp	0.68	3	0.06	83	3	1.80	85	3	3.75
Val	2.48	3	0.23	81	3	1.10	84	3	2.50
Nonessential									
Ala	2.16	3	0.16	80	3	1.79	84	3	0.61
Asp	5.81	3	0.57	82	3	1.44	84	3	2.35
Cys	0.79	3	0.10	74	3	2.70	78	3	4.63
Glu	9.18	3	1.04	85	3	0.24	87	3	0.77
Gly	2.13	3	0.19	77	3	5.83	88	3	0.50
Pro	2.84	3	0.01	81	3	2.60	104	3	10.96
Ser	2.42	3	0.19	81	3	2.48	84	3	4.37
Tyr	1.98	1		84	1		88	1	

Minerals

	x̄	n	SD
Macro, %			
Ca	0.56	1	
Cl			
K			
Mg			
Na			
P	0.77	1	
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %	39		
STTD of P, %	48		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	4378	2	177
DE	3717	1	
ME	3369		
NE	2137		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Soybean Meal, High Protein, Expelled
AAFCO #:84.6, AAFCO 2010, p. 391
IFN #: 5-04-600

Proximate Components, %	x̄	n	SD
Dry matter	94.50	1	
Crude protein	55.97	1	
Crude fiber			
Ether extract	5.13	1	
Acid ether extract			
Ash			
Carbohydrate Components, %			
Lactose			
Sucrose	4.91	1	
Raffinose	0.67	1	
Stachyose	4.58	1	
Verbascose			
Oligosaccharides			
Starch	1.89		
Neutral detergent fiber	9.99	1	
Acid detergent fiber	6.30	1	
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	55.97	1		83	1		91	1	
Arg	4.13	1		93	1		97	1	
His	1.39	1		89	1		93	1	
Ile	2.42	1		89	1		92	1	
Leu	4.09	1		89	1		92	1	
Lys	3.33	1		89	1		93	1	
Met	0.72	1		89	1		92	1	
Phe	2.71	1		90	1		93	1	
Thr	1.96	1		81	1		89	1	
Trp	0.71	1		87	1		92	1	
Val	2.59	1		86	1		91	1	
Nonessential									
Ala	2.21	1		83	1		91	1	
Asp	6.10	1		86	1		89	1	
Cys	0.80	1		77	1		84	1	
Glu	9.82	1		87	1		89	1	
Gly	2.27	1		73	1		82	1	
Pro	2.74	1		80	1		121	1	
Ser	2.50	1		86	1		92	1	
Tyr	1.88	1		87	1		91	1	

Minerals	x̄	n	SD
Macro, %			
Ca	0.29	1	
Cl			
K			
Mg			
Na			
P	0.63	1	
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %	39		
STTD of P, %	48		

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg	x̄	n	SD
GE	4784	1	
DE	3717	1	
ME	3336		
NE	2129		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Soybean Meal, Low Oligosaccharide, Dehulled, Solvent Extracted
AAFCO #: 84.7, AAFCO 2010, p. 391
IFN #: 5-04-612

Proximate Components, %

	x̄	n	SD
Dry matter	88.64	7	1.84
Crude protein	51.84	7	1.96
Crude fiber	3.10	7	0.3
Ether extract	1.14	7	0.23
Acid ether extract			
Ash	6.70	7	0.27

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose	6.38	6	1.25
Raffinose	0.13	7	0.1
Stachyose	0.43	7	0.36
Verbascose			
Oligosaccharides	0.50	5	0.44
Starch			
Neutral detergent fiber	6.30	2	0.71
Acid detergent fiber	2.55	2	0.21
Hemicellulose	3.75	2	0.92
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility AID			Digestibility SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	51.84	7	1.96	82	69	5.03	87	68	4.48
Arg									
His									
Ile									
Leu									
Lys									
Met									
Phe									
Thr									
Trp									
Val									
Nonessential									
Ala									
Asp									
Cys									
Glu									
Gly									
Pro									
Ser									
Tyr									

Minerals

	x̄	n	SD
Macro, %			
Ca			
Cl			
K			
Mg			
Na			
P			
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %	0.29	2	0.19
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	3985	3	233
DE			
ME			
NE			

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Soybean Meal, Low Oligosaccharide, Expelled
AAFCO #:84.6, AAFCO 2010, p. 391
IFN #: 5-04-600

Proximate Components, %

	x̄	n	SD
Dry matter	94.60	1	
Crude protein	49.33	1	
Crude fiber			
Ether extract	4.62	1	
Acid ether extract			
Ash			

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose	7.10	1	
Raffinose	0.18	1	
Stachyose	1.55	1	
Verbascose			
Oligosaccharides			
Starch	1.89		
Neutral detergent fiber	9.98	1	
Acid detergent fiber	6.81	1	
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	49.33	1		84	1		92	1	
Arg	3.77	1		94	1		98	1	
His	1.29	1		90	1		93	1	
Ile	2.24	1		89	1		93	1	
Leu	3.75	1		89	1		93	1	
Lys	3.12	1		89	1		93	1	
Met	0.68	1		89	1		92	1	
Phe	2.47	1		90	1		93	1	
Thr	1.81	1		81	1		88	1	
Trp	0.66	1		88	1		93	1	
Val	2.43	1		86	1		91	1	
Nonessential									
Ala	2.07	1		83	1		90	1	
Asp	5.66	1		86	1		90	1	
Cys	0.78	1		79	1		85	1	
Glu	8.94	1		87	1		90	1	
Gly	2.11	1		72	1		90	1	
Pro	2.47	1		82	1		124	1	
Ser	2.24	1		86	1		92	1	
Tyr	1.71	1		87	1		91	1	

Minerals

	x̄	n	SD
Macro, %			
Ca	0.29	1	
Cl			
K			
Mg			
Na			
P	0.63	1	
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %	39		
STTD of P, %	48		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	4737	1	
DE	3679	1	
ME	3344		
NE	2151		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Soybean Meal, Solvent Extracted
AAFCO #: 84.61, AAFCO 2010, p. 391
IFN #:5-04-604

Proximate Components, %	x̄	n	SD
Dry matter	88.79	12	0.70
Crude protein	43.90	29	1.97
Crude fiber	6.60	1	
Ether extract	1.24	6	0.25
Acid ether extract			
Ash	6.38	3	0.24
Carbohydrate Components, %			
Lactose			
Sucrose	7.63	2	0.72
Raffinose	0.90	2	0.13
Stachyose	4.32	2	0.28
Verbascose	0.12	1	
Oligosaccharides			
Starch	1.89		
Neutral detergent fiber	9.82	7	1.5
Acid detergent fiber	6.66	5	1.75
Hemicellulose			
Acid detergent lignin			
Total dietary fiber	17.48	1	
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	43.90	29	1.97	80	13	5.08	85	12	2.95
Arg	3.17	27	0.19	90	23	4.03	92	22	4.09
His	1.26	29	0.14	84	24	5.28	86	23	5.81
Ile	1.96	29	0.19	84	24	4.15	88	23	5.08
Leu	3.43	29	0.26	83	24	3.87	86	23	4.28
Lys	2.76	28	0.24	85	24	2.54	88	23	3.12
Met	0.60	27	0.06	85	21	4.71	89	20	5.21
Phe	2.26	29	0.16	85	24	3.43	87	23	3.50
Thr	1.76	28	0.13	78	24	4.34	83	23	5.62
Trp	0.59	23	0.26	85	14	4.81	90	14	4.04
Val	1.93	29	0.35	79	24	4.08	84	23	4.05
Nonessential									
Ala	1.92	25	0.18	79	19	4.55	86	19	5.04
Asp	4.88	25	0.73	83	19	3.91	86	19	3.68
Cys	0.68	23	0.20	76	13	6.81	84	13	4.98
Glu	7.87	25	1.15	86	19	3.59	88	19	3.38
Gly	1.89	25	0.20	70	19	9.31	83	19	5.92
Pro	2.43	24	0.46	74	16	18.14	98	16	11.49
Ser	2.14	25	0.28	81	19	4.19	89	19	6.17
Tyr	1.55	25	0.21	83	20	10.09	86	20	10.33

Minerals	x̄	n	SD
Macro, %			
Ca	0.35	12	0.09
Cl	0.05		
K	1.96		
Mg	0.29	2	0.00
Na	0.01	2	0.00
P	0.64	14	0.07
S	0.39	2	0.03
Micro, ppm			
Cr			
Cu	17.38	2	0.62
Fe	235	2	75.38
I			
Mn	40.64	2	9.29
Se	0.32		
Zn	50.00		
Phytate P, %	0.36	4	0.03
ATTD of P, %	39	10	4.23
STTD of P, %	48	10	4.85

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene	0.2		
Vitamin E	2.3		
Water Soluble			
Vitamin B_6	6.0		
Vitamin B_{12}, μg/kg	0		
Biotin	0.27		
Folacin	1.37		
Niacin	34		
Pantothenic acid	16.0		
Riboflavin	2.9		
Thiamin	4.5		
Choline	2794		
Energy, kcal/kg			
GE	4257	3	168
DE	3681	1	
ME	3382		
NE	2148		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	1.22		
C-12:0	0.00		
C-14:0	0.25		
C-16:0	8.20		
C-16:1	0.25		
C-18:0	2.79		
C-18:1	16.89		
C-18:2	38.52		
C-18:3	5.16		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	11.23		
MUFA	17.13		
PUFA	43.69		
IV	99.26		
IVP	12.11		

TABLE 17-1 Continued

Ingredient: Soybeans, Full Fat
AAFCO #: 84.1, AAFCO 2010, p. 390
IFN #: 5-04-596

Proximate Components, %

	x̄	n	SD
Dry matter	92.36	8	1.98
Crude protein	37.56	23	1.99
Crude fiber	4.07	1	
Ether extract	20.18	6	1.47
Acid ether extract	15.03	2	0.66
Ash	4.89	3	0.09

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose	6.42	3	1.02
Raffinose	0.77	3	0.21
Stachyose	3.89	3	0.19
Verbascose	0.03	1	
Oligosaccharides			
Starch	1.89		
Neutral detergent fiber	10.00	4	2.16
Acid detergent fiber	6.17	4	0.71
Hemicellulose			
Acid detergent lignin			
Total dietary fiber	31.45	2	4.17
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	37.56	23	1.99	74	22	8.44	79	22	9.88
Arg	2.45	22	0.51	84	22	7.93	87	22	8.36
His	0.88	22	0.16	78	22	7.78	81	22	8.06
Ile	1.60	22	0.21	75	22	8.34	78	22	9.26
Leu	2.67	22	0.47	75	22	9.80	78	22	10.36
Lys	2.23	22	0.29	79	22	9.13	81	22	9.72
Met	0.55	18	0.17	75	17	9.23	80	17	9.39
Phe	1.74	22	0.27	77	22	9.72	79	22	10.49
Thr	1.42	22	0.20	71	22	8.49	76	22	9.64
Trp	0.49	11	0.13	79	6	8.67	82	6	9.89
Val	1.73	22	0.17	73	22	8.19	77	22	9.47
Nonessential									
Ala	1.59	18	0.19	74	19	8.05	79	19	9.89
Asp	3.89	18	0.78	78	19	9.77	80	19	10.22
Cys	0.59	12	0.04	70	7	10.72	76	7	13.74
Glu	6.05	18	1.29	81	19	7.50	84	19	7.85
Gly	1.52	18	0.17	69	19	9.34	81	19	8.50
Pro	1.65	17	0.39	70	16	15.09	100	16	24.06
Ser	1.67	18	0.29	75	19	9.43	79	19	10.28
Tyr	1.20	15	0.30	77	15	10.07	81	12	10.16

Minerals

	x̄	n	SD
Macro, %			
Ca	0.31	9	0.06
Cl	0.03		
K	1.64	2	0.01
Mg	0.28		
Na	0.03		
P	0.53	9	0.04
S	0.30		
Micro, ppm			
Cr			
Cu	16.00		
Fe	80		
I			
Mn	30.00		
Se	0.11		
Zn	39.00		
Phytate P, %	0.33		
ATTD of P, %	39		
STTD of P, %	48		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene	1.9		
Vitamin E	18.1		
Water Soluble			
Vitamin B_6	10.8		
Vitamin B_{12},μg/kg	0		
Biotin	0.24		
Folacin	3.60		
Niacin	22		
Pantothenic acid	15.0		
Riboflavin	2.6		
Thiamin	11.0		
Choline	2307		

Energy, kcal/kg

	x̄	n	SD
GE	5227	5	283
DE	4193	1	
ME	3938		
NE	2874		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	21.62		
C-12:0	0.00		
C-14:0	0.28		
C-16:0	10.62		
C-16:1	0.28		
C-18:0	3.57		
C-18:1	21.81		
C-18:2	49.79		
C-18:3	6.67		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	14.46		
MUFA	22.09		
PUFA	56.46		
IV	128.24		
IVP	277.25		

TABLE 17-1 Continued

Ingredient: Soybeans, High Protein, Full Fat
AAFCO #: 84.1, AAFCO 2010, p. 390
IFN #: 5-04-596

Proximate Components, % / **Carbohydrate Components, %**

	x̄	n	SD
Dry matter	92.38	5	3.09
Crude protein	42.77	5	4.18
Crude fiber			
Ether extract	15.59	5	1.5
Acid ether extract			
Ash			
Carbohydrate Components, %			
Lactose			
Sucrose	4.75	2	0.08
Raffinose	0.85	2	0.49
Stachyose	4.01	2	0.15
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber	8.24	2	0.62
Acid detergent fiber	5.40	1	
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility AID			Digestibility SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	42.77	5	4.18	82	2	1.27	92	2	2.83
Arg	3.16	5	0.52	93	2	0.64	97	2	2.62
His	1.07	5	0.14	88	2	0.14	92	2	1.27
Ile	1.51	5	0.5	88	2	0.21	92	2	1.77
Leu	3.34	5	0.79	87	2	0.07	91	2	1.63
Lys	2.50	5	0.33	88	2	0.14	92	2	0.78
Met	0.57	5	0.08	88	2	0.28	92	2	2.62
Phe	2.25	5	0.06	89	2	0.49	93	2	1.70
Thr	1.57	5	0.08	78	2	2.33	87	2	0.42
Trp	0.48	2	0.21	85	2	1.06	89	2	0.99
Val	1.76	5	0.39	84	2	0.35	90	2	2.26
Nonessential									
Ala	1.88	2	0.02	82	2	0.21	90	2	3.25
Asp	5.15	2	0.14	87	2	0.99	91	2	0.28
Cys	0.61	5	0.05	75	2	0.35	83	2	2.62
Glu	8.12	2	0.27	88	2	1.13	91	2	0.21
Gly	1.89	2	0	68	2	8.06	91	2	3.54
Pro	2.11	2	0.09	61	2	3.11	124	2	41.51
Ser	2.04	2	0.24	84	2	1.06	91	2	0.78
Tyr	1.51	5	0.1	88	2	1.20	92	2	2.12

Minerals

	x̄	n	SD
Macro, %			
Ca	0.28	1	
Cl			
K			
Mg			
Na			
P	0.65	1	
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %	39		
STTD of P, %	48		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	5306	1	
DE			
ME			
NE			

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Soybeans, Low Oligosaccharide, Full Fat
AAFCO #: 84.1, AAFCO 2010, p. 390
IFN #: 5-04-596

Proximate Components, %	x̄	n	SD
Dry matter	94.40	1	
Crude protein	39.30	1	
Crude fiber			
Ether extract	17.70	1	
Acid ether extract			
Ash			
Carbohydrate Components, %			
Lactose			
Sucrose	5.80	1	
Raffinose	0.10	1	
Stachyose	1.40	1	
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber	10.30	1	
Acid detergent fiber	7.50	1	
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total x̄	Total n	Total SD	AID x̄	AID n	AID SD	SID x̄	SID n	SID SD
Essential									
CP	39.30	1		82	1		89	1	
Arg	2.79	1		93	1		96	1	
His	1.02	1		90	1		92	1	
Ile	1.88	1		88	1		91	1	
Leu	3.01	1		88	1		91	1	
Lys	2.56	1		90	1		93	1	
Met	0.56	1		90	1		92	1	
Phe	1.96	1		89	1		92	1	
Thr	1.44	1		83	1		88	1	
Trp	0.61	1		84	1		87	1	
Val	1.96	1		85	1		90	1	
Nonessential									
Ala	1.66	1		85	1		90	1	
Asp	4.45	1		89	1		92	1	
Cys	0.65	1		81	1		85	1	
Glu	6.83	1		90	1		92	1	
Gly	1.67	1		77	1		90	1	
Pro	1.92	1		70	1		102	1	
Ser	1.67	1		87	1		91	1	
Tyr	1.40	1		88	1		91	1	

Minerals	x̄	n	SD
Macro, %			
Ca	0.36	1	
Cl			
K			
Mg			
Na			
P	0.60	1	
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %	39		
STTD of P, %	48		

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12},μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg	x̄	n	SD
GE	5282	1	
DE			
ME			
NE			

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Soy Protein Concentrate
AAFCO #: 84.12, AAFCO 2010, p. 390
IFN #: 5-32-183

Proximate Components, %

	x̄	n	SD
Dry matter	92.64	12	1.87
Crude protein	65.20	21	4.08
Crude fiber	3.42	7	0.65
Ether extract	1.05	6	0.61
Acid ether extract	0.65	5	0.41
Ash	6.11	10	0.58

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose	0.67	3	0.35
Raffinose	0.46	2	0.44
Stachyose	0.91	2	0.06
Verbascose			
Oligosaccharides	2.46	1	
Starch	1.89		
Neutral detergent fiber	8.10	3	1.15
Acid detergent fiber	4.42	1	
Hemicellulose			
Acid detergent lignin			
Total dietary fiber	18.87	3	2.06
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	65.20	21	4.08	85	10	3.65	89	10	1.32
Arg	4.75	18	0.20	93	12	2.43	95	12	1.92
His	1.70	18	0.08	89	12	3.18	91	12	2.82
Ile	2.99	18	0.15	89	12	3.13	91	12	2.65
Leu	5.16	18	0.20	89	12	3.19	91	12	2.52
Lys	4.09	19	0.31	89	12	3.35	91	12	2.84
Met	0.87	16	0.08	90	11	2.63	92	11	2.29
Phe	3.38	18	0.16	88	12	3.62	90	12	3.30
Thr	2.52	19	0.15	82	12	4.89	86	12	3.99
Trp	0.81	13	0.27	85	10	3.91	88	10	3.29
Val	3.14	18	0.17	87	12	3.52	90	12	2.76
Nonessential									
Ala	2.82	15	0.11	85	11	4.77	89	11	2.79
Asp	7.58	15	0.36	86	11	3.99	88	11	3.64
Cys	0.90	16	0.14	75	11	4.35	79	11	5.36
Glu	12.02	15	0.65	90	11	3.72	91	11	3.07
Gly	2.75	15	0.11	79	11	9.83	88	11	2.40
Pro	3.58	14	0.36	77	10	22.44	102	10	8.13
Ser	3.33	15	0.26	88	11	4.58	91	11	3.04
Tyr	2.26	12	0.10	89	6	3.94	93	6	3.49

Minerals

	x̄	n	SD
Macro, %			
Ca	0.32	5	0.05
Cl			
K			
Mg			
Na			
P	0.82	5	0.07
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %	39		
STTD of P, %	48		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	4605	2	148
DE	4260	1	
ME	3817		
NE	2376		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	0.46		
C-12:0	0.00		
C-14:0	0.22		
C-16:0	8.26		
C-16:1	0.22		
C-18:0	2.83		
C-18:1	16.96		
C-18:2	38.48		
C-18:3	5.22		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	11.30		
MUFA	17.17		
PUFA	43.70		
IV	99.36		
IVP	4.57		

TABLE 17-1 Continued

Ingredient: Soy Protein Isolate
AAFCO #: 84.62, AAFCO 2010, p. 392
IFN #: 5-24-811

Proximate Components, %	x̄	n	SD
Dry matter	93.71	3	1.75
Crude protein	84.78	7	4.12
Crude fiber	0.17	3	0.11
Ether extract	2.76	3	1.84
Acid ether extract			
Ash	4.17	2	0.69
Carbohydrate Components, %			
Lactose			
Sucrose	0.13	1	
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides	0.37	1	
Starch	1.89		
Neutral detergent fiber	0.19	1	
Acid detergent fiber	0.00	1	
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	84.78	7	4.12	84	4	4.15	89	4	5.86
Arg	6.14	9	0.38	93	6	3.33	94	6	4.06
His	2.19	9	0.14	86	6	6.21	88	6	6.65
Ile	3.83	9	0.32	86	6	9.41	88	6	9.62
Leu	6.76	6	0.48	88	6	6.06	89	6	6.07
Lys	5.19	8	0.27	90	6	3.83	91	6	3.93
Met	1.11	9	0.20	84	5	11.49	86	5	12.11
Phe	4.40	9	0.25	87	6	5.53	88	6	6.09
Thr	3.09	9	0.27	79	6	8.20	83	6	8.42
Trp	1.13	5	0.07	84	2	0.21	87	2	2.89
Val	4.02	9	0.20	83	6	9.91	86	6	10.21
Nonessential									
Ala	3.54	5	0.26	86	5	5.39	90	5	4.22
Asp	9.64	5	0.67	90	5	3.74	92	5	2.98
Cys	0.98	7	0.06	74	3	10.21	79	3	12.18
Glu	16.00	5	1.45	93	5	3.66	94	5	3.53
Gly	3.54	5	0.27	80	5	8.98	89	5	3.12
Pro	4.45	5	0.62	83	4	9.65	113	4	29.34
Ser	4.37	5	0.66	90	5	4.67	93	5	3.28
Tyr	3.08	4	0.21	86	4	11.04	88	4	11.56

Minerals	x̄	n	SD
Macro, %			
Ca	0.17	4	0.03
Cl	0.02		
K	0.16	3	0.03
Mg	0.05	3	0.01
Na	1.14	2	0.01
P	0.75	4	0.02
S			
Micro, ppm			
Cr			
Cu	12.90	3	0.45
Fe	15.61	3	4.00
I			
Mn	11.90	3	1.40
Se	0.14		
Zn	40.26	3	3.84
Phytate P, %			
ATTD of P, %	39		
STTD of P, %	48		

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6	5.4		
Vitamin B_{12}, μg/kg	0		
Biotin	0.30		
Folacin	2.5		
Niacin	6		
Pantothenic acid	4.2		
Riboflavin	1.7		
Thiamin	0.3		
Choline	2		

Energy, kcal/kg			
GE	5386		
DE	4150		
ME	3573		
NE	2187		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	3.39		
C-12:0	0.00		
C-14:0	0.24		
C-16:0	9.14		
C-16:1	0.24		
C-18:0	3.07		
C-18:1	18.79		
C-18:2	42.86		
C-18:3	5.75		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	12.45		
MUFA	19.03		
PUFA	48.61		
IV	110.42		
IVP	37.43		

TABLE 17-1 Continued

Ingredient: Sugar Beet Pulp
AAFCO #: 63.36, AAFCO 2010, p. 380
IFN #: 4-00-669

Proximate Components, %

	x̄	n	SD
Dry matter	87.60	1	
Crude protein	9.10	1	
Crude fiber			
Ether extract	0.97		
Acid ether extract			
Ash	6.70	1	

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	0.00		
Neutral detergent fiber	44.90	1	
Acid detergent fiber	23.50	1	
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility AID			Digestibility SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	9.10	1		34					
Arg	0.32			44			54		
His	0.23			46			56		
Ile	0.31			41			55		
Leu	0.53			44			54		
Lys	0.52			48			54		
Met	0.07			52			61		
Phe	0.30			38			49		
Thr	0.38			16			29		
Trp	0.10			36			47		
Val	0.45			32			42		
Nonessential									
Ala	0.43			36			47		
Asp	0.73			16			26		
Cys	0.06			31			46		
Glu	0.89			46			59		
Gly	0.38			24			46		
Pro	0.41			21			46		
Ser	0.44			20			34		
Tyr	0.40			46			52		

Minerals

	x̄	n	SD
Macro, %			
Ca	0.81	2	0.27
Cl	0.10		
K	0.61		
Mg	0.22		
Na	0.20		
P	0.09	1	
S	0.31		
Micro, ppm			
Cr			
Cu	11.00		
Fe	411		
I			
Mn	46.00		
Se	0.09		
Zn	12.00		
Phytate P, %			
ATTD of P, %	50		
STTD of P, %	63		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene	10.6		
Vitamin E	13.2		
Water Soluble			
Vitamin B_6	1.9		
Vitamin B_{12}, μg/kg	0		
Biotin			
Folacin			
Niacin	18		
Pantothenic acid	1.3		
Riboflavin	0.7		
Thiamin	0.4		
Choline	1734		

Energy, kcal/kg

GE	4039		
DE	2865		
ME	2803		
NE	1734		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Sunflower, Full Fat
AAFCO #: 71.221, AAFCO 2010, p. 386
IFN #:5-30-032

Proximate Components, %

	x̄	n	SD
Dry matter	96.83	2	1.09
Crude protein	16.60	4	1.16
Crude fiber	13.10	3	0.43
Ether extract	42.69	3	2.02
Acid ether extract			
Ash	3.25	3	0.25

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	2.04		
Neutral detergent fiber	23.23	4	2.43
Acid detergent fiber	16.93	4	2.10
Hemicellulose			
Acid detergent lignin	4.52	2	0.17
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	16.60	4	1.16						
Arg	1.72	1					89		
His	0.55	1					84		
Ile	0.90	1					81		
Leu	1.36	1					83		
Lys	0.54	2	0.07				77		
Met	0.39	2	0.03				85		
Phe	1.02	1					84		
Thr	0.85	1					76		
Trp							77		
Val	0.94	1					78		
Nonessential									
Ala	0.95	1							
Asp	2.13	1							
Cys	0.24						73		
Glu	4.54	1							
Gly	1.24	1							
Pro									
Ser	1.00	1							
Tyr	0.55	1					86		

Minerals

	x̄	n	SD
Macro, %			
Ca	0.30	1	
Cl			
K			
Mg			
Na			
P	0.20	1	
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %	20		
STTD of P, %	29		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, µg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	6163	2	473
DE	4517		
ME	4404		
NE	3561		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	49.57		
C-12:0	0.00		
C-14:0	0.10		
C-16:0	5.64		
C-16:1	0.10		
C-18:0	4.44		
C-18:1	18.87		
C-18:2	65.83		
C-18:3	0.14		
C-18:4			
C-20:0	0.00		
C-20:1	0.10		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	10.18		
MUFA	19.07		
PUFA	65.97		
IV	136.66		
IVP	677.44		

TABLE 17-1 Continued

Ingredient: Sunflower Meal, Dehulled, Solvent Extracted
AAFCO #: 71.211, AAFCO 2010, p. 386
IFN #: 5-30-034

Proximate Components, %

	x̄	n	SD
Dry matter	90.40	2	0.14
Crude protein	39.86	8	4.78
Crude fiber	18.44	2	2.53
Ether extract	2.90		
Acid ether extract			
Ash	6.06	2	0.89

Carbohydrate Components, %

	x̄	n	SD
Lactose	0.00	2	0.00
Sucrose	0.00	2	0.00
Raffinose	0.00	2	0.00
Stachyose	0.00	2	0.00
Verbascose	0.00	2	0.00
Oligosaccharides			
Starch	2.08	2	1.03
Neutral detergent fiber	30.24	2	0.27
Acid detergent fiber	23.00	2	2.97
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	39.86	8	4.78	76	4	6.04	81	4	5.31
Arg	3.32	6	0.27	91	5	3.43	93	5	3.35
His	0.93	6	0.10	82	5	6.48	85	5	6.28
Ile	1.54	6	0.18	78	5	6.19	80	5	6.15
Leu	2.47	6	0.11	77	5	5.36	80	5	5.27
Lys	1.45	6	0.10	75	5	4.25	78	5	5.13
Met	0.78	5	0.17	84	4	3.84	89		
Phe	1.63	6	0.23	79	5	7.47	81	5	7.11
Thr	1.37	6	0.06	72	5	8.48	77	5	8.54
Trp	0.48	2	0.04	73	2	3.39	80		
Val	1.76	6	0.21	76	5	8.37	79	5	8.06
Nonessential									
Ala	1.63	3	0.09	68	3	2.17	72	3	3.62
Asp	3.55	3	0.21	74	3	1.22	77	3	1.51
Cys	0.48	4	0.21	77	3	3.89	82	3	3.42
Glu	8.25	3	0.74	84	3	0.70	86	3	1.05
Gly	2.09	3	0.13	63	3	4.30	70	3	4.95
Pro	2.01	3	0.61	63	3	16.86	81	3	10.91
Ser	1.66	3	0.10	72	3	3.19	76	3	4.86
Tyr	0.81	3	0.17	72	3	6.07	84		

Minerals

	x̄	n	SD
Macro, %			
Ca	0.39	1	
Cl	0.04		
K	1.27		
Mg	0.75		
Na	0.04		
P	1.16	1	
S	0.38		
Micro, ppm			
Cr			
Cu	25		
Fe	200		
I			
Mn	35		
Se	0.32		
Zn	98		
Phytate P, %	0.89	1	
ATTD of P, %	20		
STTD of P, %	29	1	

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	9.1		
Water Soluble			
Vitamin B_6	13.7		
Vitamin B_{12}, μg/kg	0		
Biotin	1.45		
Folacin	1.14		
Niacin	220		
Pantothenic acid	24.0		
Riboflavin	3.6		
Thiamin	3.5		
Choline	3150		

Energy, kcal/kg

	x̄	n	SD
GE	4415	2	54
DE	2840		
ME	2569		
NE	1482		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	1.70		
C-12:0	0.00		
C-14:0	0.15		
C-16:0	4.73		
C-16:1	0.30		
C-18:0	3.23		
C-18:1	15.23		
C-18:2	48.68		
C-18:3	0.23		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.00		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	8.10		
MUFA	15.53		
PUFA	48.90		
IV	102.69		
IVP	17.46		

TABLE 17-1 Continued

Ingredient: Sunflower Meal, Solvent Extracted
AAFCO #: 71.221, AAFCO 2010, p. 386
IFN #:5-30-032

Proximate Components, %

	x̄	n	SD
Dry matter	87.93	3	0.55
Crude protein	30.70	12	2.63
Crude fiber	23.40	4	2.90
Ether extract	3.06	4	0.43
Acid ether extract			
Ash	5.97	4	0.26
Carbohydrate Components, %			
Lactose	0.00	2	0.00
Sucrose	0.00	2	0.00
Raffinose	0.00	2	0.00
Stachyose	0.00	2	0.00
Verbascose	0.00	2	0.00
Oligosaccharides			
Starch	2.03	1	
Neutral detergent fiber	36.82	3	2.73
Acid detergent fiber	28.67	3	2.85
Hemicellulose			
Acid detergent lignin	7.54	1	
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility AID			Digestibility SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	30.70	12	2.63	77	6	5.06	83	6	4.64
Arg	2.53	10	0.22	91	6	2.94	93	6	2.80
His	0.78	10	0.06	80	6	4.97	83	6	5.14
Ile	1.29	10	0.06	79	6	2.96	82	6	2.62
Leu	1.96	10	0.12	79	6	3.05	82	6	2.79
Lys	1.13	10	0.07	76	6	3.33	80	6	3.71
Met	0.74	9	0.04	88	5	2.66	90	5	2.56
Phe	1.39	10	0.08	83	6	4.39	86	6	3.95
Thr	1.17	10	0.06	75	6	5.50	80	6	4.53
Trp	0.39	8	0.04	80	3	4.33	84		
Val	1.51	10	0.09	76	6	5.00	79	6	4.37
Nonessential									
Ala	1.32	8	0.07	74	3	6.31	80	3	4.92
Asp	2.68	8	0.41	80	3	3.75	84	3	3.17
Cys	0.53	9	0.06	76	3	4.88	80	3	4.09
Glu	6.12	8	0.47	86	3	2.53	88	3	2.07
Gly	1.76	8	0.08	65	3	5.96	74	3	5.47
Pro	1.29	4	0.12	79			87		
Ser	1.36	8	0.06	76	3	5.09	81	3	3.56
Tyr	0.70	9	0.14	83	4	5.23	88	4	5.04

Minerals

	x̄	n	SD
Macro, %			
Ca	0.38	3	0.04
Cl	0.10		
K	1.07		
Mg	0.68		
Na	0.02		
P	0.95	3	0.09
S	0.30		
Micro, ppm			
Cr			
Cu	26.00		
Fe	254		
I			
Mn	41.00		
Se	0.50		
Zn	66.00		
Phytate P, %	0.84	1	
ATTD of P, %	20		
STTD of P, %	29	2	7.39

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	9.1		
Water Soluble			
Vitamin B_6	11.1		
Vitamin B_{12}, μg/kg	0		
Biotin	1.40		
Folacin	1.14		
Niacin	264		
Pantothenic acid	29.9		
Riboflavin	3.0		
Thiamin	3.0		
Choline	3791		

Energy, kcal/kg

	x̄	n	SD
GE	4086	1	
DE	2010		
ME	1801		
NE	937		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	1.61		
C-12:0	0.00		
C-14:0	0.06		
C-16:0	4.60		
C-16:1	0.06		
C-18:0	3.66		
C-18:1	15.47		
C-18:2	53.91		
C-18:3	0.12		
C-18:4			
C-20:0	0.00		
C-20:1	0.06		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	8.32		
MUFA	15.59		
PUFA	54.04		
IV	111.93		
IVP	18.02		

TABLE 17-1 Continued

Ingredient: Triticale
AAFCO #: No official definition
IFN #: 4-20-362

Proximate Components, %

	x̄	n	SD
Dry matter	88.48	5	1.69
Crude protein	13.60	8	1.89
Crude fiber	2.54	2	0.22
Ether extract	1.77	2	0.47
Acid ether extract			
Ash	2.95	2	1.49
Carbohydrate Components, %			
Lactose	0.00	1	
Sucrose	0.00	1	
Raffinose	0.00	1	
Stachyose	0.00	1	
Verbascose	0.00	1	
Oligosaccharides			
Starch	64.31	2	3.80
Neutral detergent fiber	10.28	5	0.96
Acid detergent fiber	3.45	5	0.39
Hemicellulose			
Acid detergent lignin	0.77	1	
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total x̄	Total n	Total SD	AID x̄	AID n	AID SD	SID x̄	SID n	SID SD
Essential									
CP	13.60	8	1.89	79	6	4.45	87	5	3.27
Arg	0.73	4	0.20	81	8	5.26	85	6	6.61
His	0.31	4	0.05	80	7	6.48	82	7	7.18
Ile	0.45	4	0.09	79	8	5.66	83	8	6.83
Leu	0.86	4	0.20	81	8	4.42	85	8	5.50
Lys	0.46	4	0.05	74	8	7.13	78	8	9.33
Met	0.24	4	0.05	83	8	4.19	89		
Phe	0.52	4	0.19	81	7	6.51	85	7	7.75
Thr	0.41	4	0.09	64	8	11.62	70	8	14.66
Trp	0.16	3	0.03	76	3	9.43	82		
Val	0.59	4	0.13	77	8	5.68	82	8	6.98
Nonessential									
Ala	0.54	4	0.10	72	7	4.70	78	7	6.47
Asp	0.80	4	0.13	75	7	5.21	80	7	4.45
Cys	0.29	4	0.09	80	7	7.67	83	7	5.45
Glu	3.75	4	0.82	89	7	4.89	91	7	4.53
Gly	0.56	4	0.11	67	7	9.53	83	7	15.61
Pro	1.06	1		82	4	4.34	104	5	22.43
Ser	0.64	4	0.12	77	7	6.47	82	7	7.52
Tyr	0.39	4	0.11	79	6	6.39	82	6	7.00

Minerals

	x̄	n	SD
Macro, %			
Ca	0.04	9	0.01
Cl	0.03		
K	0.46		
Mg	0.10		
Na	0.03		
P	0.33	10	0.05
S	0.15		
Micro, ppm			
Cr			
Cu	8.00		
Fe	31.00		
I			
Mn	43.00		
Se			
Zn	32.00		
Phytate P, %	0.21	5	0.02
ATTD of P, %	50	6	3.52
STTD of P, %	56	6	3.50

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	1.7		
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin	0.4		
Thiamin			
Choline	462		
Energy, kcal/kg			
GE	4316		
DE	3320		
ME	3228		
NE	2507		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	2.09		
C-12:0	0.67		
C-14:0	0.43		
C-16:0	13.11		
C-16:1	0.86		
C-18:0	1.48		
C-18:1	8.52		
C-18:2	40.81		
C-18:3	2.92		
C-18:4			
C-20:0	0.00		
C-20:1	0.72		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	15.69		
MUFA	10.10		
PUFA	43.73		
IV	90.95		
IVP	19.01		

TABLE 17-1 Continued

Ingredient: Triticale DDGS
AAFCO #: No official definition

Proximate Components, %	x̄	n	SD
Dry matter	89.30	1	
Crude protein	27.42	1	
Crude fiber			
Ether extract	4.82	1	
Acid ether extract			
Ash	3.93	1	
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber	26.43	1	
Acid detergent fiber	12.23	1	
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	27.42	1							
Arg									
His									
Ile									
Leu									
Lys									
Met									
Phe									
Thr									
Trp									
Val									
Nonessential									
Ala									
Asp									
Cys									
Glu									
Gly									
Pro									
Ser									
Tyr									

Minerals	x̄	n	SD
Macro, %			
Ca	0.06	1	
Cl			
K	0.88	1	
Mg	0.29	1	
Na	0.01	1	
P	0.70	1	
S	0.29	1	
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %	56		
STTD of P, %	61		

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			
Energy, kcal/kg			
GE			
DE			
ME			
NE			

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Wheat, Hard Red

Many of the citations did not distinguish the type of wheat. We classified hard wheat as having 11% CP or greater.

AAFCO #: No official definition

IFN #: 4-05-258

Proximate Components, %

	x̄	n	SD
Dry matter	88.67	46	3.22
Crude protein	14.46	64	2.51
Crude fiber	2.57	6	0.80
Ether extract	1.82	36	0.37
Acid ether extract	2.51	3	1.16
Ash	1.98	25	0.37

Carbohydrate Components, %

	x̄	n	SD
Lactose	0.00	1	
Sucrose	0.00	1	
Raffinose	0.00	1	
Stachyose	0.00	1	
Verbascose	0.00	1	
Oligosaccharides			
Starch	59.50	26	4.32
Neutral detergent fiber	10.60	26	2.87
Acid detergent fiber	3.55	21	0.97
Hemicellulose			
Acid detergent lignin	0.97	2	0.23
Total dietary fiber	9.83	10	2.37
Insoluble dietary fiber	6.81	9	0.41
Soluble dietary fiber	2.34	9	0.86

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	14.46	64	2.51	77	13	9.54	88	12	9.12
Arg	0.60	30	0.14	83	15	5.04	91	15	5.27
His	0.34	31	0.10	83	15	7.46	88	15	6.30
Ile	0.47	31	0.10	82	15	5.97	89	15	5.69
Leu	0.91	31	0.15	83	15	5.24	89	15	4.98
Lys	0.39	34	0.08	72	15	11.73	82	15	11.31
Met	0.22	29	0.04	83	13	6.49	88	13	6.42
Phe	0.64	31	0.13	85	15	4.09	90	15	4.31
Thr	0.40	32	0.07	71	15	10.61	84	15	9.30
Trp	0.17	19	0.05	82	6	5.65	88	6	4.23
Val	0.58	31	0.10	79	15	6.07	88	15	5.91
Nonessential									
Ala	0.47	27	0.11	72	14	10.44	83	14	9.33
Asp	0.71	26	0.16	73	14	9.80	84	14	9.02
Cys	0.33	26	0.11	83	11	6.87	89	11	6.74
Glu	3.88	26	1.03	88	14	8.44	93	14	5.43
Gly	0.57	27	0.14	70	14	13.89	92	14	13.85
Pro	1.36	22	0.39	78	10	18.00	105	10	27.75
Ser	0.60	27	0.11	81	14	8.67	89	14	7.87
Tyr	0.36	26	0.11	80	15	8.22	88	14	8.16

Minerals

	x̄	n	SD
Macro, %			
Ca	0.06	25	0.05
Cl	0.06		
K	0.49	10	0.06
Mg	0.16	10	0.01
Na	0.01	10	0.00
P	0.39	37	0.10
S	0.16	10	0.01
Micro, ppm			
Cr			
Cu	3.00	10	1.15
Fe	71	10	33.88
I			
Mn	33.30	10	6.43
Se	0.33		
Zn	31.00	9	5.61
Phytate P, %	0.22	14	0.07
ATTD of P, %	46		
STTD of P, %	56		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene	0.4		
Vitamin E	11.6		
Water Soluble			
Vitamin B_6	3.4		
Vitamin B_{12}, μg/kg	0		
Biotin	0.11		
Folacin	0.22		
Niacin	48		
Pantothenic acid	9.9		
Riboflavin	1.4		
Thiamin	4.5		
Choline	778		

Energy, kcal/kg

	x̄	n	SD
GE	3788	25	145
DE	3313		
ME	3215		
NE	2472		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	1.54		
C-12:0	0.00		
C-14:0	0.06		
C-16:0	15.19		
C-16:1	0.52		
C-18:0	0.84		
C-18:1	12.47		
C-18:2	38.96		
C-18:3	1.75		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	16.10		
MUFA	12.99		
PUFA	40.71		
IV	87.03		
IVP	13.40		

TABLE 17-1 Continued

Ingredient: Wheat, Soft Red

Many of the citations did not distinguish the type of wheat. We classified soft wheat as having less than 11% CP.

AAFCO #: No official definition

IFN #: 4-05-294

Proximate Components, %

	x̄	n	SD
Dry matter	86.38	5	1.69
Crude protein	10.92	5	0.48
Crude fiber			
Ether extract	1.36	3	0.06
Acid ether extract			
Ash	1.99	1	

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	60.04	3	1.91
Neutral detergent fiber			
Acid detergent fiber	3.55		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber	9.90	3	1.07
Insoluble dietary fiber	6.63	3	0.4
Soluble dietary fiber	3.27	3	0.82

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	10.92	5	0.48						
Arg	0.52	2	0.08	83			89		
His	0.28	2	0.01	84			90		
Ile	0.34	2	0.04	84			90		
Leu	0.68	2	0.09	85			87		
Lys	0.35	2	0	73			82		
Met	0.22	2	0.01	85			90		
Phe	0.52	2	0.04	87			91		
Thr	0.35	2	0.02	72			85		
Trp	0.14	2	0.02	81			88		
Val	0.47	2	0.08	80			87		
Nonessential									
Ala	0.42	1							
Asp	0.58	1							
Cys	0.30	2	0	84			90		
Glu	2.92	1							
Gly	0.49	1							
Pro	1.04	1							
Ser	0.44	1							
Tyr	0.30	2	0.04	84			88		

Minerals

	x̄	n	SD
Macro, %			
Ca	0.03	4	0.00
Cl	0.08		
K	0.46		
Mg	0.11		
Na	0.01		
P	0.30	5	0.03
S	0.16		
Micro, ppm			
Cr			
Cu	8.00		
Fe	32		
I			
Mn	38.00		
Se	0.28		
Zn	47.00		
Phytate P, %	0.20	4	0.03
ATTD of P, %	46		
STTD of P, %	56	4	4.71

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6	2.2		
Vitamin B_{12}, μg/kg	0		
Biotin	0.11		
Folacin	0.35		
Niacin	48		
Pantothenic acid	9.9		
Riboflavin	1.4		
Thiamin	4.5		
Choline	1092		

Energy, kcal/kg

GE	4295		
DE	3450		
ME	3376		
NE	2595		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	1.56		
C-12:0	0.00		
C-14:0	0.13		
C-16:0	17.37		
C-16:1	0.51		
C-18:0	0.90		
C-18:1	10.90		
C-18:2	40.26		
C-18:3	1.79		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	18.40		
MUFA	11.41		
PUFA	42.05		
IV	88.07		
IVP	13.74		

TABLE 17-1 Continued

Ingredient: Wheat Bran
AAFCO #: 93.1, AAFCO 2010, p. 407
IFN #: 4-05-190

Proximate Components, %	x̄	n	SD
Dry matter	87.38	8	0.55
Crude protein	15.08	10	1.08
Crude fiber	7.77	7	1.40
Ether extract	4.72	7	0.58
Acid ether extract			
Ash	4.16	7	0.59
Carbohydrate Components, %			
Lactose	0.00	7	0.00
Sucrose	0.00	7	0.00
Raffinose	0.00	7	0.00
Stachyose	0.00	7	0.00
Verbascose	0.00	7	0.00
Oligosaccharides			
Starch	22.56	4	7.44
Neutral detergent fiber	32.28	5	6.77
Acid detergent fiber	11.00	6	1.61
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	15.08	10	1.08	69	2	10.57	78	2	4.96
Arg	0.77	2	0.44	78	2	3.71	90	2	7.04
His	0.39	2	0.07	68	2	7.75	76	2	2.19
Ile	0.47	2	0.08	72			75	2	3.90
Leu	0.80	2	0.25	61	2	17.76	73	2	8.27
Lys	0.52	2	0.05	61	2	25.05	73	2	17.68
Met	0.22	2	0.07	67	1		72	1	
Phe	0.49	2	0.21	74	2	9.68	83	2	6.26
Thr	0.60	2	0.13	48	2	20.94	64	2	6.68
Trp	0.22			59	1		73	1	
Val	0.66	2	0.14	70	2	14.19	79	2	9.41
Nonessential									
Ala	1.79	2	1.11	52			58		
Asp	3.38	2	3.07	63	2	15.60	66		
Cys	0.74	1		70			77		
Glu	5.03	2	5.42	84	2	6.79	84		
Gly	1.44	2	0.83	57	2	31.54	67		
Pro	0.00	1		80	2	10.78	87		
Ser	1.52	2	1.18	67	2	16.51	73		
Tyr	0.69	2	0.55	51	2	32.92	56	1	

Minerals	x̄	n	SD
Macro, %			
Ca	0.10	3	0.02
Cl	0.07		
K	1.26		
Mg	0.52		
Na	0.04		
P	0.99	3	0.15
S	0.22		
Micro, ppm			
Cr			
Cu	14.00		
Fe	170		
I			
Mn	113		
Se	0.51		
Zn	100		
Phytate P, %	0.88	1	
ATTD of P, %	46		
STTD of P, %	56		

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene	1.0		
Vitamin E	16.5		
Water Soluble			
Vitamin B_6	12.0		
Vitamin B_{12}, µg/kg	0		
Biotin	0.36		
Folacin	0.63		
Niacin	186		
Pantothenic acid	31.0		
Riboflavin	4.6		
Thiamin	8.0		
Choline	1232		
Energy, kcal/kg			
GE	4010	7	66
DE	2420		
ME	2318		
NE	1646		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	4.25		
C-12:0	0.05		
C-14:0	0.16		
C-16:0	13.08		
C-16:1	0.40		
C-18:0	0.87		
C-18:1	14.56		
C-18:2	47.98		
C-18:3	3.93		
C-18:4			
C-20:0	0.00		
C-20:1	0.00		
C-20:4	0.12		
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA	14.16		
MUFA	14.96		
PUFA	52.02		
IV	111.46		
IVP	47.37		

TABLE 17-1 Continued

Ingredient: Wheat DDGS
AAFCO #: 27.6, AAFCO 2010, p. 343
IFN #: 5-05-194

Proximate Components, %	x̄	n	SD
Dry matter	92.59	20	1.77
Crude protein	36.61	23	2.78
Crude fiber	6.75	4	1.12
Ether extract	5.34	18	1.56
Acid ether extract	5.09	1	
Ash	4.57	11	0.38

Carbohydrate Components, %	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	1.78	6	1.00
Neutral detergent fiber	34.7	16	8
Acid detergent fiber	13.81	17	3.12
Hemicellulose			
Acid detergent lignin	4.45	1	
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total x̄	Total n	Total SD	AID x̄	AID n	AID SD	SID x̄	SID n	SID SD
Essential									
CP	36.61	23	2.78	69	10	4.82	75	10	4.96
Arg	1.41	13	0.20	76	9	5.36	82	9	4.32
His	0.76	13	0.09	72	10	5.33	75	10	5.37
Ile	1.25	13	0.10	69	10	4.95	73	10	6.34
Leu	2.45	13	0.23	77	10	3.84	80	10	4.02
Lys	0.73	15	0.17	44	11	13.66	51	10	11.14
Met	0.52	11	0.10	70	8	7.34	78		
Phe	1.67	13	0.17	82	10	3.08	84	10	2.97
Thr	1.13	15	0.13	64	11	6.05	71	10	5.45
Trp	0.37	7	0.04	72	5	5.85	77	5	5.68
Val	1.60	13	0.12	69	10	4.63	73	10	5.21
Nonessential									
Ala	1.35	9	0.13	64	6	2.73	70	6	2.11
Asp	1.85	9	0.23	52	6	5.72	59	6	5.59
Cys	0.61	8	0.15	69	5	11.31	76	5	8.75
Glu	9.59	9	1.65	79	6	13.34	87	6	1.52
Gly	1.48	9	0.18	59	6	8.05	72	6	4.24
Pro	3.34	9	0.53	68	6	12.32	90	6	7.86
Ser	1.69	9	0.26	71	6	2.68	77	6	2.96
Tyr	1.06	7	0.05	77	5	4.27	81	5	3.82

Minerals	x̄	n	SD
Macro, %			
Ca	0.16	7	0.04
Cl			
K	1.06	1	
Mg	0.39	1	
Na	0.28	1	
P	0.92	9	0.05
S	0.44	1	
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %	0.21	2	0.04
ATTD of P, %	56	3	5.98
STTD of P, %	61	3	5.86

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg	x̄	n	SD
GE	4650	12	165
DE	3151	6	321
ME	2902		
NE	1847		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	6.50		
C-12:0	0.00		
C-14:0	0.07		
C-16:0	11.57		
C-16:1	0.26		
C-18:0	0.52		
C-18:1	9.88		
C-18:2	36.66		
C-18:3	3.84		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.85		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	12.16		
MUFA	10.99		
PUFA	40.50		
IV	86.66		
IVP	56.33		

TABLE 17-1 Continued

Ingredient: Wheat Gluten
AAFCO #: No official definition

Proximate Components, %	x̄	n	SD
Dry matter			
Crude protein	72.11	9	3.94
Crude fiber			
Ether extract			
Acid ether extract			
Ash			
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch			
Neutral detergent fiber			
Acid detergent fiber			
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	72.11	9	3.94	89	1		91	1	
Arg	2.67	9	0.28	83	1		85	1	
His	1.66	9	0.36	86	1		87	1	
Ile	2.66	9	0.18	86	1		87	1	
Leu	5.06	9	0.21	90	1		91	1	
Lys	1.27	9	0.22	78	1		80	1	
Met	1.08	9	0.14	83	1		85	1	
Phe	3.91	9	0.32	88	1		89	1	
Thr	2.42	8	0.68	68	1		72	1	
Trp	1.03	8	0.46	76			83		
Val	2.88	9	0.24	83	1		85	1	
Nonessential									
Ala	2.12	1		72			79		
Asp	3.08	1		71			79		
Cys	1.48	1		70			76		
Glu	23.87	1		75			79		
Gly	2.74	1		67			79		
Pro	9.67	1		68			79		
Ser	4.07	1		69			79		
Tyr	2.42	8	0.12	72			79		

Minerals	x̄	n	SD
Macro, %			
Ca			
Cl			
K			
Mg			
Na			
P			
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg			
GE			
DE			
ME			
NE			

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.	4.00		
C-12:0	0.00		
C-14:0	0.07		
C-16:0	11.57		
C-16:1	0.26		
C-18:0	0.52		
C-18:1	9.88		
C-18:2	36.66		
C-18:3	3.84		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	0.85		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	12.16		
MUFA	10.99		
PUFA	40.50		
IV	86.66		
IVP	34.67		

TABLE 17-1 Continued

Ingredient: Wheat Middlings
AAFCO #: 93.5, AAFCO 2010, p. 407
IFN #: 4-05-205

Proximate Components, %

	$\bar{x}$	n	SD
Dry matter	89.10	22	1.51
Crude protein	15.76	22	1.36
Crude fiber	5.15	3	3.90
Ether extract	3.15	6	1.01
Acid ether extract	2.35	1	
Ash	2.05	4	0.85

Carbohydrate Components, %

	$\bar{x}$	n	SD
Lactose	0.00	2	0.00
Sucrose	0.00	2	0.00
Raffinose	0.00	2	0.00
Stachyose	0.00	2	0.00
Verbascose	0.00	2	0.00
Oligosaccharides			
Starch	21.83		
Neutral detergent fiber	34.97	17	8.52
Acid detergent fiber	5.98	4	2.91
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility AID			Digestibility SID		
	$\bar{x}$	n	SD	$\bar{x}$	n	SD	$\bar{x}$	n	SD
Essential									
CP	15.76	22	1.36						
Arg	1.10	17	0.13	87			91		
His	0.44	17	0.04	80			84		
Ile	0.51	18	0.04	77			79		
Leu	1.03	17	0.07	75			80		
Lys	0.65	18	0.05	73			78		
Met	0.25	18	0.02	78			82		
Phe	0.64	17	0.06	79			84		
Thr	0.53	18	0.03	62			73		
Trp	0.19	16	0.01	76			81		
Val	0.72	18	0.06	74			81		
Nonessential									
Ala	0.60	2	0.03	71			77		
Asp	1.04			73			79		
Cys	0.35	17	0.03	71			76		
Glu	3.10			87			91		
Gly	0.69	2	0.03	65			75		
Pro	1.72	2	0.21	79			89		
Ser	0.81	2	0.05	75			84		
Tyr	0.29			77			83		

Minerals

	$\bar{x}$	n	SD
Macro, %			
Ca	0.11	19	0.02
Cl	0.04		
K	1.06		
Mg	0.41		
Na	0.05		
P	0.98	20	0.17
S	0.17		
Micro, ppm			
Cr			
Cu	10.00		
Fe	84		
I			
Mn	100		
Se	0.53	12	0.25
Zn	92.00		
Phytate P, %	0.61	1	
ATTD of P, %	46		
STTD of P, %	56		

Vitamins, mg/kg (unless otherwise noted)

	$\bar{x}$	n	SD
Fat Soluble			
β-Carotene	3.0		
Vitamin E	20.1		
Water Soluble			
Vitamin B_6	9.0		
Vitamin B_{12}, μg/kg	0		
Biotin	0.33		
Folacin	0.76		
Niacin	72		
Pantothenic acid	15.6		
Riboflavin	1.8		
Thiamin	16.5		
Choline	1187		

Energy, kcal/kg

	$\bar{x}$	n	SD
GE	3901	2	106
DE	3075		
ME	2968		
NE	2113		

Fatty Acids, % of Ether Extract

	$\bar{x}$	n	SD
E.E.	3.60		
C-12:0	0.00		
C-14:0	0.08		
C-16:0	14.24		
C-16:1	0.32		
C-18:0	0.64		
C-18:1	12.16		
C-18:2	45.12		
C-18:3	4.72		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	1.04		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	14.96		
MUFA	13.52		
PUFA	49.84		
IV	106.66		
IVP	38.40		

TABLE 17-1 Continued

Ingredient: Wheat Screenings
AAFCO #: 81.1, AAFCO 2010, p. 389
IFN #: 4-05-216

Proximate Components, %	x̄	n	SD
Dry matter	89.88	15	1.05
Crude protein	14.91	15	0.70
Crude fiber			
Ether extract	5.73	15	1.63
Acid ether extract			
Ash			
Carbohydrate Components, %			
Lactose			
Sucrose	1.69	15	0.43
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	46.91	15	5.12
Neutral detergent fiber			
Acid detergent fiber			
Hemicellulose			
Acid detergent lignin			
Total dietary fiber	19.22	5	1.27
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	14.91	15	0.70						
Arg									
His									
Ile									
Leu									
Lys									
Met									
Phe									
Thr									
Trp									
Val									
Nonessential									
Ala									
Asp									
Cys									
Glu									
Gly									
Pro									
Ser									
Tyr									

Minerals	x̄	n	SD
Macro, %			
Ca			
Cl			
K			
Mg			
Na			
P			
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			
Energy, kcal/kg			
GE			
DE			
ME			
NE			

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Wheat Shorts
AAFCO #: 93.6, AAFCO 2010, p. 408
IFN #: 4-05-201

Proximate Components, %

	x̄	n	SD
Dry matter	87.90		
Crude protein	16.76	1	
Crude fiber			
Ether extract	4.60		
Acid ether extract			
Ash			

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	28.60		
Neutral detergent fiber	29.50	1	
Acid detergent fiber	8.60		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	16.76	1		53	1		62	1	
Arg	1.07	1		86			88		
His	0.42	1		82			84		
Ile	0.53	1		77			81		
Leu	0.97	1		72	1		83		
Lys	0.59	1		62	1		76		
Met	0.27	1		81			84		
Phe	0.62	1		82			84		
Thr	0.51	1		72			76		
Trp	0.22			77			84		
Val	0.76	1		76			81		
Nonessential									
Ala	0.91	1		67	1		74	1	
Asp	1.11	1		66	1		73	1	
Cys	0.43	1		60	1		82		
Glu	3.07	1		85	1		89	1	
Gly	0.83	1		62	1		80	1	
Pro									
Ser	0.63	1		67	1		75	1	
Tyr	0.26	1		78			84		

Minerals

	x̄	n	SD
Macro, %			
Ca	0.08	1	
Cl	0.04		
K	1.06		
Mg	0.25		
Na	0.02		
P	0.93	1	
S	0.20		
Micro, ppm			
Cr			
Cu	12.00		
Fe	100		
I			
Mn	89.00		
Se	0.75		
Zn	100		
Phytate P, %			
ATTD of P, %	46		
STTD of P, %	56		

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6	7.2		
Vitamin B_{12}, μg/kg	0		
Biotin	0.24		
Folacin	1.40		
Niacin	107		
Pantothenic acid	22.3		
Riboflavin	3.3		
Thiamin	18.1		
Choline	1170		

Energy, kcal/kg

	x̄	n	SD
GE	4505		
DE	2985		
ME	2871		
NE	2074		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.	3.50		
C-12:0	0.00		
C-14:0	0.08		
C-16:0	14.24		
C-16:1	0.32		
C-18:0	0.64		
C-18:1	12.16		
C-18:2	45.12		
C-18:3	4.72		
C-18:4	0.00		
C-20:0	0.00		
C-20:1	1.04		
C-20:4	0.00		
C-20:5	0.00		
C-22:0	0.00		
C-22:1	0.00		
C-22:5	0.00		
C-22:6	0.00		
C-24:0	0.00		
SFA	14.96		
MUFA	13.52		
PUFA	49.84		
IV	106.66		
IVP	37.33		

TABLE 17-1 Continued

Ingredient: Yeast, Brewers'
AAFCO #: 96.4, AAFCO 2010, p. 408
IFN #: 7-05-527

Proximate Components, %	x̄	n	SD
Dry matter	93.30		
Crude protein	46.52		
Crude fiber			
Ether extract	2.05		
Acid ether extract			
Ash			
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	4.20		
Neutral detergent fiber	4.00		
Acid detergent fiber	3.00		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total x̄	Total n	Total SD	AID x̄	AID n	AID SD	SID x̄	SID n	SID SD
Essential									
CP	46.52								
Arg	2.20			79			79		
His	1.09			77			77		
Ile	2.15			74			74		
Leu	3.13			73			73		
Lys	3.22			76			76		
Met	0.74			72			72		
Phe	1.83			72			72		
Thr	2.20			63			66		
Trp	0.56			60			60		
Val	2.39			70			70		
Nonessential									
Ala									
Asp									
Cys	0.50			38			48		
Glu									
Gly									
Pro									
Ser									
Tyr	1.55			61			64		

Minerals	x̄	n	SD
Macro, %			
Ca	0.16		
Cl	0.12		
K	1.80		
Mg	0.23		
Na	0.10		
P	1.40	1	
S	0.40		
Micro, ppm			
Cr			
Cu	2.70	1	
Fe	38	1	
I			
Mn	8.80	1	
Se	1.00		
Zn	76.60	1	
Phytate P, %			
ATTD of P, %	80	1	
STTD of P, %	85	1	

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E	10.0		
Water Soluble			
Vitamin B_6	42.8		
Vitamin B_{12}, μg/kg	1		
Biotin	0.63		
Folacin	9.90		
Niacin	448		
Pantothenic acid	109		
Riboflavin	37.0		
Thiamin	91.8		
Choline	3984		

Energy, kcal/kg	x̄	n	SD
GE	4461	1	
DE	4015	1	
ME	3699		
NE	2414		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Yeast, Ethanol
AAFCO #: No official definition

Proximate Components, %	x̄	n	SD
Dry matter	93.30		
Crude protein	46.52		
Crude fiber			
Ether extract	2.05		
Acid ether extract			
Ash			
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	0.00		
Neutral detergent fiber			
Acid detergent fiber	3.00		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total x̄	Total n	Total SD	AID x̄	AID n	AID SD	SID x̄	SID n	SID SD
Essential									
CP	46.52								
Arg									
His									
Ile									
Leu									
Lys									
Met									
Phe									
Thr									
Trp									
Val									
Nonessential									
Ala									
Asp									
Cys									
Glu									
Gly									
Pro									
Ser									
Tyr									

Minerals	x̄	n	SD
Macro, %			
Ca	0.29	2	0.00
Cl			
K			
Mg			
Na			
P	0.68	2	0.01
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %	57	2	4.10
STTD of P, %	70	2	4.10

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			
Energy, kcal/kg			
GE	4648		
DE	4015		
ME	3699		
NE	2394		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Yeast, Single Cell Protein
AAFCO #: No official definition

Proximate Components, %

	x̄	n	SD
Dry matter	93.30		
Crude protein	36.25	1	
Crude fiber			
Ether extract	2.05		
Acid ether extract			
Ash			

Carbohydrate Components, %

	x̄	n	SD
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	0.00		
Neutral detergent fiber			
Acid detergent fiber	3.00		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %

	Total			Digestibility					
				AID			SID		
	x̄	n	SD	x̄	n	SD	x̄	n	SD
Essential									
CP	36.25	1		66	1		69	1	
Arg	1.45	1		73	1		75	1	
His	0.71	1		64	1		66	1	
Ile	1.36	1		57	1		59	1	
Leu	1.81	1		59	1		61	1	
Lys	2.58	1		73	1		74	1	
Met	0.84	1		87	1		88	1	
Phe	1.18	1		51	1		53	1	
Thr	1.42	1		51	1		54	1	
Trp									
Val	1.53	1		55	1		58	1	
Nonessential									
Ala	1.45	1		51	1		52	1	
Asp	2.30	1		52	1		55	1	
Cys									
Glu	3.56	1		60	1		62	1	
Gly	1.31	1		48	1		56	1	
Pro	1.10	1		55	1		65	1	
Ser	1.26	1		56	1		60	1	
Tyr	0.61	1		60	1				

Minerals

	x̄	n	SD
Macro, %			
Ca			
Cl			
K			
Mg			
Na			
P	1.54	2	0.67
S			
Micro, ppm			
Cr			
Cu			
Fe			
I			
Mn			
Se			
Zn			
Phytate P, %			
ATTD of P, %	70	2	3.25
STTD of P, %	75	2	1.31

Vitamins, mg/kg (unless otherwise noted)

	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6			
Vitamin B_{12}, μg/kg			
Biotin			
Folacin			
Niacin			
Pantothenic acid			
Riboflavin			
Thiamin			
Choline			

Energy, kcal/kg

	x̄	n	SD
GE	3725	2	1698
DE	4166	2	128
ME	3920		
NE	2593		

Fatty Acids, % of Ether Extract

	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-1 Continued

Ingredient: Yeast, Torula
AAFCO #: 96.7, AAFCO 2010, p. 408
IFN #: 7-05-534

Proximate Components, %	x̄	n	SD
Dry matter	93.30		
Crude protein	51.17	1	
Crude fiber			
Ether extract	2.05		
Acid ether extract			
Ash			
Carbohydrate Components, %			
Lactose			
Sucrose			
Raffinose			
Stachyose			
Verbascose			
Oligosaccharides			
Starch	0.00		
Neutral detergent fiber			
Acid detergent fiber	3.00		
Hemicellulose			
Acid detergent lignin			
Total dietary fiber			
Insoluble dietary fiber			
Soluble dietary fiber			

Amino Acids, %	Total x̄	Total n	Total SD	AID x̄	AID n	AID SD	SID x̄	SID n	SID SD
Essential									
CP	51.17	1							
Arg	2.99	1							
His	1.02	1							
Ile	2.26	1							
Leu	3.41	1							
Lys	3.39	1							
Met	0.64	1							
Phe	2	1							
Thr	2.28	1							
Trp	0.59	1							
Val	2.72	1							
Nonessential									
Ala									
Asp									
Cys	0.52	1							
Glu									
Gly									
Pro									
Ser									
Tyr	1.65								

Minerals	x̄	n	SD
Macro, %			
Ca	0.58		
Cl	0.12		
K	1.94		
Mg	0.20		
Na	0.07		
P	1.52		
S	0.55		
Micro, ppm			
Cr			
Cu	17.00		
Fe	222		
I			
Mn	13.00		
Se	0.01	1	
Zn	99		
Phytate P, %			
ATTD of P, %			
STTD of P, %			

Vitamins, mg/kg (unless otherwise noted)	x̄	n	SD
Fat Soluble			
β-Carotene			
Vitamin E			
Water Soluble			
Vitamin B_6	36.3		
Vitamin B_{12}, µg/kg			
Biotin	0.58		
Folacin	22.4		
Niacin	492		
Pantothenic acid	84.2		
Riboflavin	49.9		
Thiamin	6.2		
Choline	2881		
Energy, kcal/kg			
GE	4718		
DE	4015		
ME	3667		
NE	2351		

Fatty Acids, % of Ether Extract	x̄	n	SD
E.E.			
C-12:0			
C-14:0			
C-16:0			
C-16:1			
C-18:0			
C-18:1			
C-18:2			
C-18:3			
C-18:4			
C-20:0			
C-20:1			
C-20:4			
C-20:5			
C-22:0			
C-22:1			
C-22:5			
C-22:6			
C-24:0			
SFA			
MUFA			
PUFA			
IV			
IVP			

TABLE 17-2 Mineral Concentrations in Macromineral Sources (data on as-fed basis)[a]

				Phosphorus									
Entry Number	Description	International Feed Number	Calcium[b] (%)	Total (%)	ATTD (%)	STTD (%)	Sodium (%)	Chlorine (%)	Potassium (%)	Magnesium (%)	Sulfur (%)	Iron (%)	Manganese (%)
1	Bone meal, steamed	6-00-400	29.8	12.5	—	—	0.04	—	0.2	0.3	2.4	—	0.03
2	Calcium carbonate	6-01-069	38.5	0.02	—	—	0.08	0.02	0.08	1.61	0.08	0.06	0.02
3	Calcium phosphate (dicalcium)	6-01-080	24.8 (25)	18.8 (26)	73.9 (16)	81.4 (16)	0.20 (4)	0.47	0.15	0.5 (4)	0.1 (4)	0.80 (4)	0.14
4	Calcium phosphate (monocalcium)	6-26-334	16.9 (14)	21.5 (15)	82.8 (14)	88.3 (14)	0.2	—	0.16	0.9	0.8	0.75	0.01
5	Calcium phosphate (tricalcium)	6-01-084	34.2 (3)	17.7 (3)	48.0 (2)	53.4 (2)	6.0 (1)	—	—	0.4 (1)	0.0 (1)	—	—
6	Calcium sulfate, dihydrate	6-01-090	21.85	—	—	—	—	—	—	0.48	16.19	—	—
7	Limestone, ground[c]	6-02-632	35.84	0.01	—	—	0.06	0.02	0.11	2.06	0.04	0.35	0.02
8	Magnesium carbonate	6-02-754	0.02	—	—	—	—	—	—	30.2	—	—	0.01
9	Magnesium oxide	6-02-756	1.69	—	—	—	—	—	0.02	55	0.1	1.06	—
10	Magnesium phosphate	6-23-294	10.1 (1)	19.7 (1)	83.9 (1)	98.2 (1)	—	—	—	—	—	—	—
11	Magnesium sulfate, heptahydrate	6-02-758	0.02	—	—	—	—	0.01	0	9.6	13.04	—	—
12	Phosphate, defluorinated	6-01-780	32	18	—	—	3.27	—	0.1	0.29	0.13	0.84[d]	0.05
13	Phosphate, monoammonium	6-09-338	0.35	24.2	—	—	0.2	—	0.16	0.75	1.5	0.41	0.01
14	Phosphate, rock curacao, ground	6-05-586	35.09	14.23	—	—	0.2	—	—	0.8	—	0.35	—
15	Phosphate, rock, soft	6-03-947	16.09	9.05	—	—	0.1	—	—	0.38	—	1.92	0.1
16	Potassium chloride	6-03-755	0.05	—	—	—	1	46.93	51.37	0.23	0.32	0.06	0.001
17	Potassium and magnesium sulfate	6-06-177	0.06	—	—	—	0.76	1.25	18.45	11.58	21.97	0.01	0.002
18	Potassium sulfate	6-08-098	0.15	—	—	—	0.09	1.5	43.04	0.6	17.64	0.07	0.001
19	Sodium carbonate	6-12-316	—	—	—	—	43.3	—	—	—	—	—	—
20	Sodium bicarbonate	6-04-272	0.01	—	—	—	27	—	0.01	—	—	—	—
21	Sodium chloride	6-04-152	0.3	—	—	—	39.5	59	0	0.005	0.2	0.01	—
22	Sodium phosphate, dibasic	6-04-286	—	21.15	—	—	31.04	—	—	—	—	—	—
23	Sodium phosphate, monobasic	6-04-288	0.09	24.7 (4)	86.7 (4)	93.8 (4)	19.1 (1)	0.02	0.01	0.01	—	—	—
24	Sodium sulfate, decahydrate	6-04-291	—	—	—	—	13.8	—	—	—	9.7	—	—

NOTE: The mineral supplements used as feed supplements are not chemically pure compounds, and the composition may vary substantially among sources. The supplier's analysis should be used if it is available. For example, feed-grade dicalcium phosphate contains some monocalcium phosphate, and feed-grade monocalcium phosphate contains some dicalcium phosphate. Dashes indicate that no data were available.

[a]Numbers in parenthesis are the number of observations for each mean. If no observations were found in the current literature, values from NRC (1998) were used.

[b]Estimates suggest 90 to 100% bioavailability of calcium in most sources of monocalcium phosphate, dicalcium phosphate, tricalcium phosphate, defluorinated phosphate, calcium carbonate, calcium sulfate, and calcitic limestone. The calcium in high-magnesium limestone or dolomitic limestone is less bioavailable (50 to 80%).

[c]Most calcitic limestones will contain 38% or more calcium and less magnesium than shown.

[d]Iron in defluorinated phosphate is about 65% as available as the iron in ferrous sulfate.

TABLE 17-3 Inorganic Sources and Estimated Bioavailabilities of Trace Minerals[a]

Mineral Element and Source[b]	Chemical Formula	Mineral Content (%)	Relative Bioavailability (%)
Copper			
Cupric sulfate (pentahydrate)	$CuSO_4 \cdot 5H_2O$	25.2	100
Cupric chloride, tribasic	$Cu_2(OH)_3Cl$	58	100
Cupric oxide	CuO	75	0 to 10
Cupric carbonate (monohydrate)	$CuCO_3 \cdot Cu(OH)_2 \cdot H_2O$	*50 to 55*	*60 to 100*
Cupric sulfate (anhydrous)	$CuSO_4$	*39.9*	*100*
Iron			
Ferrous sulfate (monohydrate)	$FeSO_4 \cdot H_2O$	30	100
Ferrous sulfate (heptahydrate)	$FeSO_4 \cdot 7H_2O$	20	100
Ferrous carbonate	$FeCO_3$	38	15 to 80
Ferric oxide	Fe_2O_3	*69.9*	*0*
Ferric chloride (hexahydrate)	$FeCl_3 \cdot 6H_2O$	*20.7*	*40 to 100*
Ferrous oxide	FeO	*77.8*	—[c]
Iodine			
Ethylenediamine dihydroiodide (EDDI)	$C_2H_8N_22HI$	79.5	100
Calcium iodate	$Ca(IO_3)_2$	63.5	100
Potassium iodide	KI	68.8	100
Potassium iodate	KIO_3	*59.3*	—[c]
Cupric iodide	CuI	*66.6*	*100*
Manganese			
Manganous sulfate (monohydrate)	$MnSO_4 \cdot H_2O$	29.5	100
Manganous oxide	MnO	60	70
Manganous dioxide	MnO_2	*63.1*	*35 to 95*
Manganous carbonate	$MnCO_3$	*46.4*	*30 to 100*
Manganous chloride (tetrahydrate)	$MnCl_2 \cdot 4H_2O$	*27.5*	*100*
Selenium			
Sodium selenite	Na_2SeO_3	45	100
Sodium selenate (decahydrate)	$Na_2SeO_4 \cdot 10H_2O$	*21.4*	*100*
Zinc			
Zinc sulfate (monohydrate)	$ZnSO_4 \cdot H_2O$	35.5	100
Zinc oxide	ZnO	72	50 to 80
Zinc sulfate (heptahydrate)	$ZnSO_4 \cdot 7H_2O$	*22.3*	*100*
Zinc carbonate	$ZnCO_3$	*56*	*100*
Zinc chloride	$ZnCl_2$	*48*	*100*

[a]The mineral source listed first under each mineral element was generally the standard with which the other sources were compared to establish relative bioavailability.

[b]Less commonly used sources in italics.

[c] — indicates no data available.

TABLE 17-4 Characteristics and Energy Values of Various Sources of Fats and Oils (data on as-fed basis)[a]

		Fatty Acids (weight % of total fat)								
Type of Lipid	IFN	≤ C10	C12:0	C14:0	C16:0	C16:1	C18:0	C18:1	C18:2	C18:3
Animal fats										
Beef tallow	4-08-127	0	0.9	3.7	24.9	4.2	18.9	36	3.1	0.6
Choice white grease	——	0.2	0.2	1.9	21.5	5.7	14.9	41.1	11.6	0.4
Poultry	4-09-319	0	0.1	0.9	21.6	5.7	6.0	37.4	19.5	1.0
Lard	4-04-790	0.1	0.2	1.3	23.8	2.7	13.5	41.2	10.2	1.0
Restaurant grease	——	—	—	1.9	16.2	2.5	10.5	47.5	17.5	1.9
Fish oils										
Herring	7-08-048	0	0.2	7.2	11.7	9.6	0.8	12.0	1.2	0.8
Menhaden	7-08-049	0	0	8.0	15.2	10.5	3.8	14.5	2.2	1.5
Salmon	——	0	0	3.3	9.8	4.8	4.3	17.0	1.5	1.1
Sardine	——	0	0.1	6.5	16.7	7.5	3.9	14.8	2.0	1.3
Vegetable oils										
Canola	4-06-144	0	0	0	4.0	0.2	1.8	56.1	20.3	9.3
Coconut	——	5.6	43.8	16.8	8.4	0	2.5	5.9	1.7	0
Corn	4-07-882	0	0	0	10.6	0.1	1.9	27.3	53.5	1.16
Cottonseed	4-20-836	0	0	0.8	22.7	0.8	2.3	17.0	51.5	0.2
Flaxseed	——	0	0	0	5.3	0	4.1	20.2	12.7	53.3
Oat	——	0	0.4	0.2	16.7	0.2	1.1	34.9	39.1	1.8
Olive	——	0	0	0	11.3	1.3	2.0	71.3	9.8	0.8
Palm kernel	——	3.7	47.0	16.4	8.1	0	2.8	11.4	1.6	0
Peanut	4-03-658	0	0	0.1	9.5	0.1	2.2	44.8	32	0
Safflower	——	0	0	0	4.3	0	1.9	14.4	74.6	0
Sesame	——	0	0	0	8.9	0.2	4.8	39.3	41.3	0.3
Soybean	4-07-983	0	0	0.1	10.3	0.2	3.8	22.8	51	6.8
Soybean lecithin	——	0	0	0.1	12.0	0.4	2.9	10.6	40.2	5.1
Sunflower	4-20-833	0	0	0	5.4	0.2	3.5	45.3	39.8	0.2
Blends										
Animal–vegetable blend[g]	——	0	0.3	1.5	20.2	3.2	10.1	35.5	21.6	0.9

[a]Fatty acid data were obtained from the USDA Food Composition Database, Release 23 (http://www.nal.usda.gov/fnic/foodcomp/search/) except for choice white grease and restaurant grease, which were obtained from the Fats and Proteins Research Foundation (http://www.fprf.org/).

[b]Calculated from fatty acid composition (see Chapter 1).

[c]Calculated by the following relationship (Powles et al., 1995; see Chapter 3): DE (kcal/kg) = $[36.898 - (0.005 \times FFA) - (7.330 \times e^{-0.906 \times U:S})] / 0.004184$ where FFA is the free fatty acid content in g/kg and U:S is the ratio of unsaturated to saturated fatty acids. In calculating the DE, the free fatty acid concentrations of all fats were assumed to be 50 g/kg (or 5%).

[d]ME = DE × 0.98 (see Chapter 1).

[e]NE = ME × 0.88 (van Milgen et al., 2001; see Chapter 1).

[f]The concentration of coconut oil was calculated from the digestibility (89.42% of GE) reported by Cera et al. (1989) for pigs from 2 to 4 weeks after weaning at 3 weeks of age.

[g]Animal-vegetable blend = 25% lard, 25% poultry fat, 25% tallow, and 25% corn oil.

C20:1	C20:4	C20:5	C22:1	C22:5	C22:6	Total Sat.	Total Unsat.	U:S Ratio	IV[b]	Energy Content (kcal/kg) DE[c]	ME[d]	NE[e]
0.3	0	0	0	0	0	48.4	44.2	0.91	44	7,995	7,835	6,895
1.8	0	0	0	0	0	40.8	59.2	1.45	60	8,290	8,124	7,149
1.1	0.1	0	0	0	0	28.7	64.8	2.26	79	8,535	8,364	7,361
1	0	0	0	0	0	38.9	56.1	1.44	62	8,288	8,123	7,148
1	0	0	0	0	0	29.9	70.1	2.34	75	8,550	8,379	7,374
13.6	0.3	6.3	20.6	0.6	4.2	19.9	71.4	3.60	109	8,692	8,519	7,496
1.3	1.2	13.2	0.4	4.9	8.6	26.9	60.9	2.27	161	8,535	8,365	7,361
3.9	0.7	13.0	3.4	3.0	18.2	17.4	69.4	3.99	195	8,713	8,538	7,514
6.0	1.8	10.1	5.6	2.0	10.7	27.2	64.7	2.38	154	8,558	8,387	7,381
1.7	0	0	0.6	0	0	7.1	88.2	12.42	115	8,759	8,384	7,554
0	0	0	0	0	0	77.0	7.59	0.11	8	7,169[f]	7,025	6,182
0.1	0	0	0	0	0	12.9	82.3	6.39	125	8,754	8,579	7,549
0	0.1	0	0	0	0	25.8	69.6	2.70	110	8,608	8,436	7,424
0	0	0	0	0	0	9.4	86.2	9.17	187	8,759	8,583	7,553
0	0	0	0	0	0	18.4	76.0	4.14	107	8,718	8,544	7,519
0.3	0	0	0	0	0	13.79	83.36	6.05	85	8,752	8,577	7,548
0	0	0	0	0	0	78.0	13.0	0.17	13	7,265	7,119	6,265
1.3	0	0	0	0	0	16.9	78.2	4.63	99	8,733	8,558	7,531
0	0	0	0	0	0	6.2	89.0	14.34	148	8,759	8,584	7,554
0.2	0	0	0	0	0	13.7	81.3	5.93	111	8,751	8,576	7,547
0.2	0	0	0	0	0	14.2	81.0	5.70	132	8,749	8,574	7,545
0	0	0	0	0	0	15.0	56.3	3.75	97	8,701	8,527	7,504
0	0	0	0	0	0	8.9	85.5	9.61	114	8,760	8,585	7,555
0.6	0.03	0	0	0	0	32.2	61.8	2.75	77	8,393	8,225	7,238

Appendix A

Model User Guide

GENERAL OVERVIEW

The primary use of this program is to estimate nutrient requirements for the four different categories of swine: starting pigs, growing-finishing pigs, gestating sows, and lactating sows. Within these categories the effect of key determinants of nutrient requirements (e.g., level and stage of production) on nutrient requirements can be explored. Various aspects of animal performance, nutrient utilization, and nutrient requirements are presented graphically and are summarized in reports that can be printed.

Alternative systems can be used to characterize dietary contents of (1) energy (digestible, metabolizable, or net), (2) amino acids and nitrogen (total, apparent ileal digestible, or standardized ileal digestible), and (3) phosphorus (total, apparent total tract digestible, or standardized total tract digestible). These systems are selected before running the models to determine requirements.

The program can also be used to evaluate specific feeding programs in terms of (1) nutrient losses into the environment, which is based on nutrient balance calculations, and (2) comparing model-generated estimates of nutrient requirements with dietary nutrient levels in a feeding program. Feeding programs are phase-feeding schemes that represent specific diets and time periods or body weight ranges. Feeding programs can be generated and stored in a database for later use in the models. The program also includes a table of feed ingredients with nutrient profiles and a simple feed formulation routine. Examples of diets and feeding programs are stored in the original version of the program.

The program also allows direct comparisons between model-generated estimates of animal performance and observed performance. Confidence in model-generated estimates of nutrient requirements is generally greater when model-predicted performance is similar to observed performance. To evaluate current performance of growing-finishing pigs, information about local carcass evaluation schemes may be specified.

Detailed information about the calculations that are included in these models is provided in Chapter 8 of *Nutrient Requirements of Swine* (NRC, 2012).

A series of case studies is included with the program in a PDF file. These case studies illustrate the various segments of the program and demonstrate its features and limitations.

USING THE PROGRAM

Getting Started

To run the program, Microsoft Excel version 2002 (XP) or later is required. The program is designed to function on both Microsoft Windows and Apple operating systems. However, it will not function on Excel for Mac version 2008 which does not support Visual Basic macros. It is recommended that both the original version and a personal version (under a different name) of the program be saved. Additional versions of the program can be saved and this is advised when major changes are made to diet formulations and feeding programs. **The program includes macros and requires that macros be enabled within Excel. It is digitally signed by the National Academy of Sciences. In most cases, allowing the macros to run is simply a matter of accepting the digital signature of the National Academy of Sciences as a "trusted" source. If this does not work, macros can be enabled manually.**[1] After the program has been opened, responsibility for risk of use must be acknowledged by clicking the *Accept* button. The *Main Menu* will then be displayed. Throughout the program, context-sensitive comments can be

[1]To do this in Microsoft Excel 2007 or later, open Excel, click on the icon in the top left corner of the window, choose "Excel Options" at the bottom of the new window, choose "Trust Center," Choose "Trust Center Settings," choose "Macro Settings," and then select "Enable all macros (not recommended; potentially dangerous code can run)." After working with the models, "Macro Settings" may be returned to previous settings.

viewed by moving the curser over cells that are marked with a small red triangle.

Main Menu

The *Main Menu* (Figure A-1) is used to select nutrient systems for energy, amino acids, and phosphorus. Selections are made by clicking on the white data-entry fields to access a drop-down menu of choices. If a feeding program is to be included in the evaluation, this must be specified on the *Main Menu*. For initial use of the program it is suggested that a feeding program not be included in the evaluation. Further information on how to generate and store feeding programs is provided below. The models for the different categories of swine are selected from the *Main Menu*.

Models: Starting Pigs, Growing-Finishing Pigs, Gestating Sows, Lactating Sows

For each of the models (Figures A-2 to A-5), inputs are entered directly in the white data-entry fields or, when a limited number of options is available, by selecting one of the options that are accessed using drop-down menus in the data-entry fields. When certain options are selected, new data-entry fields are presented or hidden. For example, when alternative means to specify feed intake or to match observed with model predicted performance are selected, additional data-entry fields appear. When inputs are changed, model calculations must be executed, by clicking *Calculate* at the top of the screen. In *Starting Pigs,* calculations are conducted automatically when input values are changed.

Nutrient requirements can be explored for different body weight ranges (*Starting* and *Growing-Finishing Pigs*) or time periods (*Gestating Sows* and *Lactating Sows*), by changing values for initial and final body weight or days in the section *Results* (Figures A-2 to A-5). When altering these values, there is no need to rerun the models; the results are recalled from a table that is generated each time the model is run. Buttons at the top of the screen enable navigation to the *Main Menu*, resetting default input values, and viewing graphs and printable reports.

In the *Growing-Finishing Pigs*, *Gestating Sows*, and *Lactating Sows* models, animal performance level may be altered to match observed with model-predicted performance. For these three categories of swine, maintenance energy requirements can be adjusted. For both *Gestating Sows* and *Lactating Sows*, the composition of maternal body weight changes (e.g., the ratio between body protein and body lipid) can be altered. For *Growing-Finishing Pigs,* various options are available for manipulating the shape of the body protein deposition curve and the relationship between energy intake and body protein deposition. Some of these options are rather complex and should be used with caution. For *Growing-Finishing Pigs*, carcass evaluation parameters can be altered by clicking on *Carcass Evaluation Options*. Matching observed performance with model-predicted performance is an iterative process (i.e., by manually altering values for the adjustments, rerunning the model, and comparing newly predicted performance with observed performance until reasonable agreement is achieved).

Feeding Programs

The module *Feeding Program & Diet Generation* can be accessed from the *Main Menu*, by selecting *Yes* following *Do you wish to evaluate a feeding program*? and clicking on *Review Feeding Programs*. This part of the program contains three tables (ingredients, diets, and feeding programs) and has four submodules that are used to (1) select ingredients, (2) formulate diets, (3) review and edit the diet table, and (4) create feeding programs (Figure A-6). Navigation among these submodules is accomplished by buttons at the top of the screen.

When a feeding program is selected, the dietary contents of energy and fermentable fiber as specified in diets in feeding programs are used to estimate nutrient requirements of *Growing-Finishing Pigs*, *Gestating Sows*, and *Lactating Sows*. In this case, specific feeding programs are chosen in the section *Inputs* of each of these models (Figure A-4a).

1. Select Ingredients

In this submodule, the data-entry fields under the heading *Ingredient* are used to access a drop-down menu that lists feed ingredients included in the ingredient library, which is taken from Chapter 17 in *Nutrient Requirements of Swine* (NRC, 2012; click on *Ingredient Library* to review its content).[2] After a feed ingredient has been selected and loaded, its nutrient profile may be altered by changing values in columns U to BT. Values that are changed are highlighted in a different color. Special attention should be given to values that are in blue; these are consistent with the nutrient systems that are specified on the *Main Menu*. Additional ingredients may be entered in the database by typing a new ingredient name in column D and entering the appropriate nutrient levels in the relevant columns. The first ingredient in the ingredient list is used as the residual feed ingredient that must be included in all diets and is used to ensure that the inclusion levels of all feed ingredients totals 100%. Once ingredients are included in diets they cannot be replaced by other ingredients in the database. To replace *Corn, Yellow Dent* as the residual ingredient in the original version of the program, all diets and feeding programs must be deleted. Ingredients can be removed from the database by using the

[2] In the ingredient library, fermentable (i.e., apparent fecal digestible) fiber is included as an additional characteristic of ingredients. This characteristic is not included in NRC (2012) and is required to estimate fermentative threonine losses and thus to estimate threonine requirements, as outlined in Chapter 8 of *Nutrient Requirements of Swine* (NRC, 2012). Estimates for this characteristic were obtained from CVB (2004).

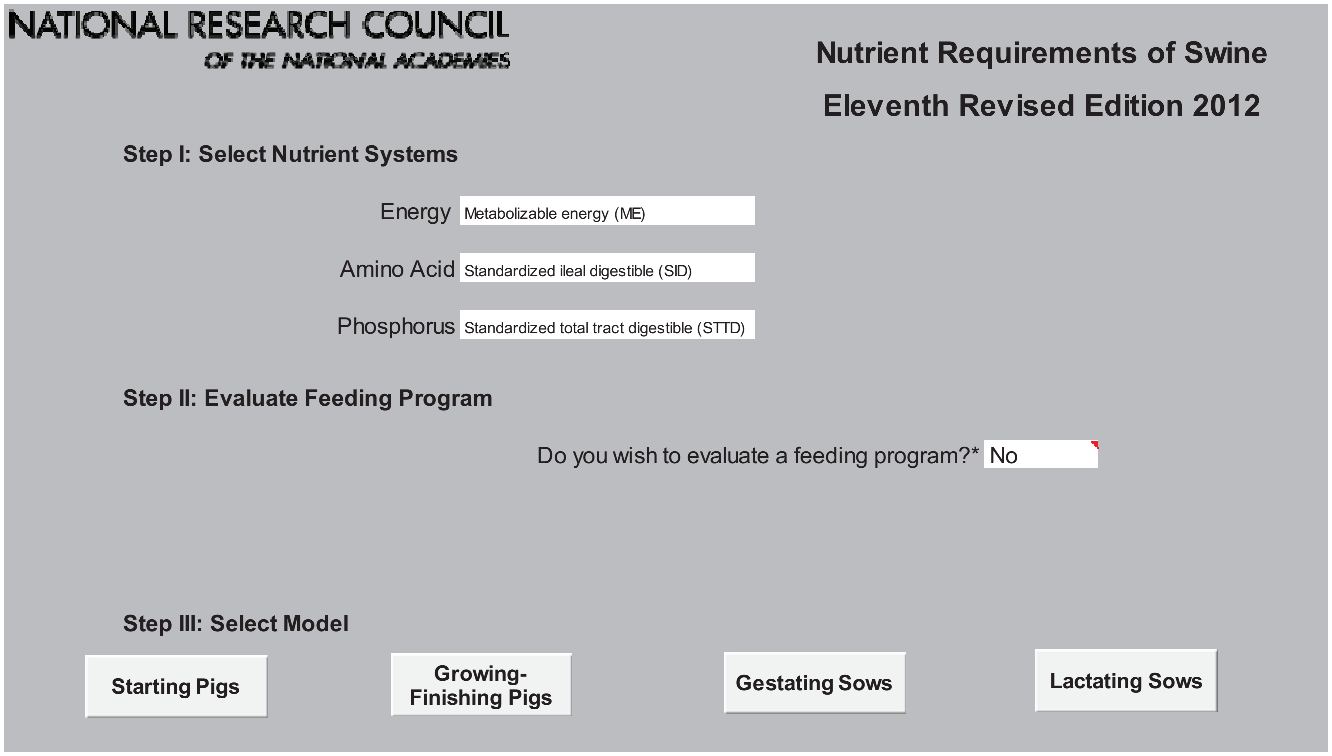

FIGURE A-1 Main menu.

drop-down menu and selecting *Clear* at the bottom of the list. A maximum of 50 ingredients can be included in the database.

2. Formulate Diet

In this section diets are formulated. When the data-entry field under Select Diet is selected, a pull-down menu is displayed that lists all formulated diets that are included in the database. New diets can be generated by entering a new diet name in the data-entry field. In the data-entry fields below *Ingredient*, ingredients can be selected from the ingredient database, using pull-down menus. For all ingredients, except the residual ingredient, inclusion levels must be specified. The residual ingredient is listed as the first ingredient and is included in all diets. For this ingredient the inclusion level is calculated automatically. Dietary nutrient levels are displayed and calculated automatically when the inclusion level of an ingredient is changed. Diets can be saved or deleted by clicking the appropriate buttons. A maximum of 25 formulated diets can be stored.

3. Diet Database

The database of formulated diets is presented in this section and dietary nutrient levels are displayed. Additional diets can entered (Diets 25-60) by entering names in column D and nutrient levels in columns U to BU, thereby bypassing the diet formulation submodule.

4. Create Feeding Program

In this section, feeding programs are selected and reviewed (Figure A-6). By clicking on the data-entry field next to *Select a feeding program or type a name to create a new one,* a pull-down menu can be accessed that lists all feeding programs in the database. New feeding programs can be generated by entering a new name in the first data-entry field, and by selecting a category of swine in the second data-entry field. Start day (or weight) values can then be entered in the first column and diets can be selected in the second column. Feeding programs can be saved or deleted by clicking on the appropriate buttons. A maximum of 30 feeding programs can be stored.

Main Menu | **Report** | **Enter Default Inputs**

Starting Pigs (< 20 kg Body Weight)

Note: Estimated nutrient requirements will differ slighty from those presented in Tables 16-1 and 16-5. This is attributed to a less than perfect fit of nutrient requirement curves across the different body weight ranges.

INPUTS: Change inputs by altering values in white cells as appropriate. Results are calculated automatically. (To restore all values to defaults, click the Enter Default Inputs button.)

Mean body weight, kg	12
Diet ME content, kcal/kg	3300
Feed intake / (feed intake + wastage)	0.95

RESULTS: Energy intake and nutrient requirements

ME intake, kcal/day	2176
Daily feed intake + wastage, g/day	694

	Average SID AA requirement %	Average SID AA requirement g/day	Ratio to Lys x 100
Lys	1.285	8.47	100.0
Arg	0.585	3.86	45.5
His	0.441	2.91	34.4
Ileu	0.659	4.34	51.3
Leu	1.286	8.48	100.1
Met	0.371	2.45	28.9
Met + Cys	0.708	4.67	55.1
Phe	0.756	4.99	58.8
Phe + Tyr	1.186	7.82	92.3
Thr	0.758	5.00	59.0
Trp	0.212	1.40	16.5
Val	0.816	5.38	63.5
N	2.673	17.62	208.0
100x lysine/N x 6.25			7.69

Average calcium and phosphorus requirements

	%	g/day
Total calcium	0.74	4.86
STTD phosphorus	3.62	23.85

RESULTS: Mineral and vitamin requirements

	Level in diet		Daily amount	
Sodium	0.30	%	2.00	g/day
Chloride	0.36	%	2.38	g/day
Magnesium	0.04	%	0.26	g/day
Potassium	0.27	%	1.76	g/day
Copper	5.3	mg/kg	3.49	mg/day
Iodine	0.14	mg/kg	0.09	mg/day
Iron	100	mg/kg	65.9	mg/day
Manganese	3.3	mg/kg	2.17	mg/day
Selenium	0.3	mg/kg	174	µg/day
Zinc	86	mg/kg	57	mg/day
Vitamin A	1879	IU/kg	1239	IU/day
Vitamin D	206	IU/kg	136	IU/day
Vitamin E	12	IU/kg	8.2	IU/day
Vitamin K	0.50	mg/kg	0.33	mg/day
Biotin	0.05	mg/kg	0.03	mg/day
Choline	0.44	g/kg	0.29	g/day
Folacin	0.30	mg/kg	0.20	mg/day
Niacin, available	30.0	mg/kg	19.8	mg/day
Pantothenic acid	9.4	mg/kg	6.2	mg/day
Riboflavin	3.1	mg/kg	2.1	mg/day
Thiamin	1.0	mg/kg	0.68	mg/day
Vitamin B_6	4.1	mg/kg	2.7	mg/day
Vitamin B_{12}	16	µg/kg	10.5	µg/day
Linoleic acid	0.10	%	0.66	g/day

FIGURE A-2 Inputs and results for the starting pigs module.

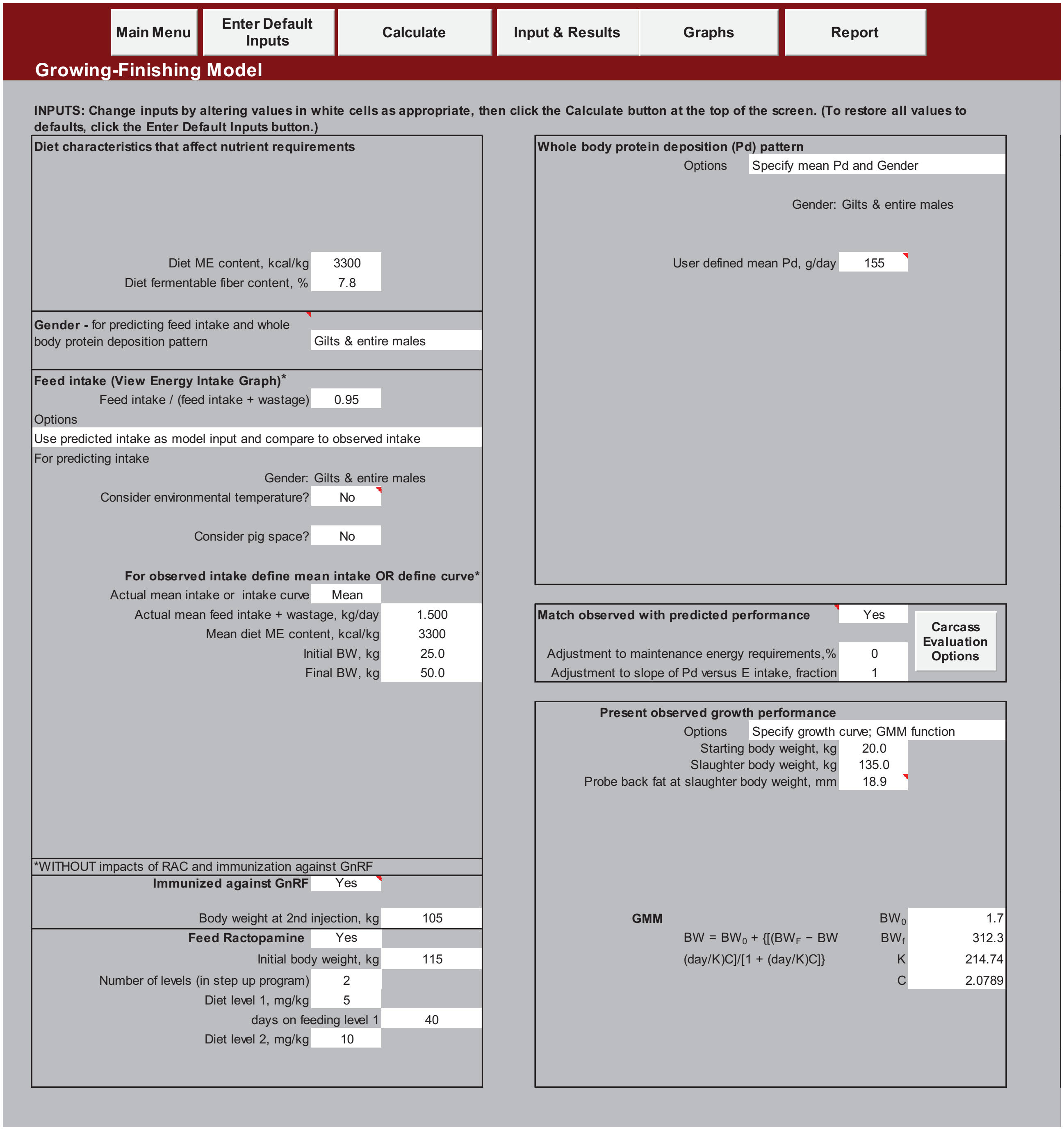

FIGURE A-3a Inputs for the growing-finishing pig model.

Growing-Finishing Model

RESULTS: Data for specific weight ranges may be examined by changing the Initial body weight and Final body weight below.

Feed intake curve for model input	Entire males	
Pd curve shape for model input	Entire males	
Mean Pd, 25 to 125 kg body weight, g/day	155.0	
Feed intake curve for observed performance	Actual & Reference	
Growth curve for observed performance	GMM	
	Predicted	**Observed**
Starting body weight, kg	20.0	19.6
Slaughter body weight, kg	136.6	136.5
Days to slaughter body weight	130	133
Probe back fat at slaughter body wt, mm	15.3	16.0
Average overall lean tissue gain, g/day	353	338

Range in body weight for estimating nutrient requirements

Initial body weight, kg	50		
Final body weight, kg	75		
Initial body weight (data base), kg	49.6	49.9	
Final body weight (data base), kg	75.3	75.9	
Days from intial to final body weight	29	28	
Days after immunization at final body weight	0		
Days on Ractopamine at final body weight	0		
Average diet ME content, kcal/kg	3300	3300	
Average ME intake, kcal/day	6458		
Average intake, % of reference intake	92.6		
Average whole body protein deposition, g/day	153		
Average whole body lipid deposition, g/day	200		
Average lean tissue gain, g/day	390		
Average daily feed intake + wastage, kg/day	2.060	2.101	
Average body weight gain, g/day	885	931	Diet at initial
Average gain:feed intake + wastage	0.429	0.443	body weight

Average SID AA requirement

	%	g/day	Ratio to Lys x 100	- %
Lys	0.892	17.4	100.0	-
Arg	0.408	8.0	45.7	-
His	0.306	6.0	34.4	-
Ile	0.467	9.1	52.3	-
Leu	0.899	17.6	100.8	-
Met	0.257	5.0	28.9	-
Met + Cys	0.504	9.9	56.6	-
Phe	0.533	10.4	59.8	-
Phe + Tyr	0.838	16.4	94.0	-
Thr	0.544	10.6	61.0	-
Trp	0.153	3.0	17.1	-
Val	0.580	11.4	65.1	-
N	1.922	37.6	215.6	-
100xLys/Nx6.25			7.4	

Average calcium and phosporus requirements

	%	g/day	
Total calcium	0.654	12.81	-
STTD phosphorus	0.304	5.96	-

Nutrient balances

Initial body weight, kg	49.6
Final body weight, kg	75.3

	Nitrogen	Phosphorus	Carbon
Intake & wastage, kg/pig	-	-	-
Retention, kg/pig	-	-	-
Retention, % of intake	-	-	-
Excretion, kg/pig	-	-	-

Mineral and vitamin requirements

Mean body weight, kg	62.4
Mean feed intake, kg/day	1.957

	Level in diet		Daily amount	
Sodium	0.11	%	2.13	g/day
Chloride	0.09	%	1.68	g/day
Magnesium	0.04	%	0.84	g/day
Potassium	0.20	%	3.99	g/day
Copper	0.36	mg/kg	7.10	mg/day
Iodine	0.02	mg/kg	0.29	mg/day
Iron	5.12	mg/kg	100.10	mg/day
Manganese	2.1	mg/kg	4.19	mg/day
Selenium	0.2	mg/kg	341	μg/day
Zinc	56	mg/kg	110	mg/day
Vitamin A	1393	IU/kg	2727	IU/day
Vitamin D	161	IU/kg	315	IU/day
Vitamin E	12	IU/kg	23.07	IU/day
Vitamin K	0.54	mg/kg	1.05	mg/day
Biotin	0.05	mg/kg	0.10	mg/day
Choline	0.32	g/kg	0.63	g/day
Folacin	0.32	mg/kg	0.63	mg/day
Niacin, available	32.2	mg/kg	62.92	mg/day
Pantothenic acid	7.8	mg/kg	15.21	mg/day
Riboflavin	2.3	mg/kg	4.46	mg/day
Thiamin	1.1	mg/kg	2.10	mg/day
Vitamin B_6	1.1	mg/kg	2.10	mg/day
Vitamin B_{12}	6.7	μg/kg	13.12	μg/day
Linoleic acid	0.11	%	2.10	g/day

FIGURE A-3b Results for the growing-finishing pig model.

Main Menu | Enter Default Inputs | Calculate | Input & Results | Graphs | Report

Gestation Model

INPUTS: Change inputs by altering values in white cells as appropriate, then click the Calculate button at the top of the screen. (To restore all values to defaults, click the Enter Default Inputs button.)

Diet characteristics that affect nutrient requirements

Select feeding program: Gest CoSBM

For diet energy and fermentable fiber levels, see tab 'Feeding program.'

Sow performance

Sow body weight at breeding, kg	165
Parity	2
Gestation length, d	114
Anticipated litter size	13.5
Anticipated birth weight, kg/pig	1.40

Feed Intake (View Energy Intake Graph)

Feed intake / (feed intake + feed wastage): 0.95

Start day	1	30	60	90
Feed intake + feed wastage, kg/day	2.210	2.210	2.210	2.610
Diet name	:oSBM Early Ges	:SBM Early Ge	CoSBM Early Ges	:oSBM Late Ge

Consider housing conditions & environmental temperature: Yes

Sows standing, min/d (typical value 240 min/d): 240

Housing: Individual

Effective environmental temperature: 20 Celsius

Match observed with predicted performance: Yes

	Observed		Model predicted
Body weight at farrowing, kg	225		**225.0**
P2 backfat at breeding, mm	18.0	default = 18	**18.0**
P2 backfat at farrowing, mm	20.0		**20.5**
Change in body weight during gestation, kg	**60.0**		**60.0**
Change in P2 backfat during gestation, mm	**2.0**		**2.5**

Adjustment to maintenance energy requirements, %	0.00	default = 0; range -10 to +20
Abs. adjustm. to maternal body N gain (g/extra Mcal ME intake)	0.00	default = 0; range 0 to 2

FIGURE A-4a Inputs for the gestating sow model.

Gestation Model

RESULTS: Data for specific time periods during gestation may be examined by changing the Initial day and Final day below.

Range in days for estimating nutrient requirements (start gestation is d 1)

Initial day	1	
Final day	114	
Initial total sow body weight	165.0	kg
Final total sow body weight	224.6	kg
Average ME intake	7203	kcal/d
Average diet ME content	3300	kcal/kg
Average feed intake + feed wastage	2.298	kg/day
Average total sow body weight gain	526	g/day
Average maternal sow body weight gain	318	g/day
Avg total sow body protein deposition inc conceptus	68.0	g/day
Average maternal sow body protein deposition	47.0	g/day
Average protein deposition in conceptus	21.0	g/day
Avg total sow body lipid deposition including conceptus	100	g/day
Average maternal sow body lipid deposition	96	g/day
Average lipid deposition in conceptus	3.80	g/day
Current diet according to feeding program on final day	CoSBM Late Gest	
Current diet ME content on final day, kcal/kg	3300	

	Average SID AA requirement		Ratio to	Diet on final day
	%	g/day	Lys x 100	%
Lys	0.476	10.4	100.0	0.65
Arg	0.250	5.5	52.5	0.78
His	0.159	3.5	33.5	0.34
Ile	0.268	5.9	56.3	0.49
Leu	0.441	9.6	92.5	1.18
Met	0.133	2.9	28.0	0.22
Met+Cys	0.316	6.9	66.4	0.43
Phe	0.265	5.8	55.7	0.61
Phe+Tyr	0.461	10.1	96.8	0.99
Thr	0.356	7.8	74.7	0.43
Trp	0.090	2.0	18.8	0.13
Val	0.345	7.5	72.3	0.56
N	1.252	27.3	262.7	1.93
100 x Lys/ N x 6.25			6.1	

Average calcium and phosphorus requirements

	%	g/day	
Total calcium	0.602	13.15	0.67
STTD phosphorus	0.262	5.72	0.35

Nutrient balance over entire gestation period

	Nitrogen	Phosphorus	Carbon
Intake & wastage, kg/sow	5.27	1.50	102.4
Retention, kg/sow	1.24	0.35	12.8
Retention, % of intake	23.52	23.36	12.5
Excretion, kg/sow	4.03	1.15	89.6

Mineral and vitamin requirements

	Level in diet		Daily amount	
Sodium	0.14	%	3.15	g/day
Chloride	0.12	%	2.52	g/day
Magnesium	0.06	%	1.26	g/day
Potassium	0.19	%	4.2	g/day
Copper	10	mg/kg	21	mg/day
Iodine	0.13	mg/kg	0.29	mg/day
Iron	77	mg/kg	168	mg/day
Manganese	24	mg/kg	52	mg/day
Selenium	0.14	mg/kg	315	µg/day
Zinc	96	mg/kg	210	mg/day
Vitamin A	3847	IU/kg	8398	IU/d
Vitamin D	769	IU/kg	1680	IU/d
Vitamin E	42	IU/kg	92	IU/d
Vitamin K	0.48	mg/kg	1.05	mg/day
Biotin	0.19	mg/kg	0.42	mg/day
Choline	1.20	g/kg	2.62	g/day
Folacin	1.25	mg/kg	2.73	mg/day
Niacin, available	9.6	mg/kg	21	mg/day
Pantothenic acid	11.5	mg/kg	25.2	mg/day
Riboflavin	3.6	mg/kg	7.9	mg/day
Thiamin	1.0	mg/kg	2.1	mg/day
Vitamin B_6	1.0	mg/kg	2.1	mg/day
Vitamin B_{12}	14.4	µg/kg	31.49	µg/day
Linoleic acid	0.10	%	2.1	g/day

FIGURE A-4b Results for the gestating sow model.

Main Menu | Enter Default Inputs | Calculate | Input & Results | Graphs | Report

Lactation Model

INPUTS: Change inputs by altering values in white cells as appropriate, then click the Calculate button at the top of the screen. (To restore all values to defaults, click the Enter Default Inputs button.)

Diet characteristics that affect nutrient requirements

Net energy (NE) content kcal/kg	2517.9
Diet fermentable fiber content, %	8.0

Sow performance

Sow body weight after farrowing, kg	210
Lactation length, days	21
Average number of pigs nursed	11.5
Daily piglet weight gain, g; mean over entire lactation	230.0

Feed Intake (View Energy Intake Graph)

Feed intake / (feed intake + feed wastage)	0.95	
Use model predicted feed intakes?	Yes	
Parity number	2 And Higher	
Consider environmental temperature?	Yes	
Effective environmental temperature	25	Celsius

`

Match observed with predicted performance? Yes

	Observed		Model predicted
Body weight at weaning, kg	195		**197.0**
P2 backfat at farrowing, mm	20	default = 20	**20.0**
P2 backfat at weaning, mm	17		**17.2**
Change in body weight during lactation, kg	**-15.0**		**-13.0**
Change in P2 back fat during lactation, mm	**-3.0**		**-2.8**

Adjustment to maintenance energy requirements, %	0	default = 0; range -20 to +40
Protein:lipid energy ratio in body energy balance	0.12	default = 0.12; range 0 to 0.20

FIGURE A-5a Inputs for the lactating sow model.

Lactation Model

RESULTS: Data for specific time periods during lactation may be examined by changing the Initial day and Final day below.

Range in days for estimating nutrient requirements (start lactation is d 1)

Initial day	1
Final day	21
Initial sow body weight, kg	210.0
Final sow body weight, kg	197.0
Average NE intake, kcal/day	14046
Average diet NE content, kcal/kg	2518
Average feed intake + feed wastage, kg/day	5.872
Average sow body weight gain, g/day	-620
Average sow whole body protein deposition, g/day	-62
Average sow whole body lipid deposition, g/day	-309
Average milk production, kg/day	9.1
Current diet according to feeding program on final day	-
Current diet NE content on final day, kcal/kg	

Average AID AA requirement	%	g/day	Ratio to Lys x 100	Diet on final day %
Lys	0.779	43.4	100.0	-
Arg	0.391	21.8	50.2	-
His	0.305	17.0	39.2	-
Ile	0.429	23.9	55.0	-
Leu	0.886	49.4	113.8	-
Met	0.206	11.5	26.4	-
Met+Cys	0.413	23.0	53.0	-
Phe	0.418	23.3	53.7	-
Phe+Tyr	0.880	49.1	113.0	-
Thr	0.466	26.0	59.8	-
Trp	0.146	8.2	18.8	-
Val	0.644	35.9	82.7	-
N	1.533	85.5	196.9	-
100 x Lys/ N x 6.25			8.13	

Average calcium and phosporus requirements

	%	g/day	
Total calcium	0.752	41.9	-
ATTD phosphorus	0.324	18.1	-

Nutrient balance over entire lactation period
(sow and litter)

	Nitrogen	Phosph.	Carbon
Intake & wastage, kg/sow	-	-	-
Retention, kg/sow	-	-	-
Retention, % of intake	-	-	-
Excretion, kg/sow	-	-	-

Mineral and vitamin requirements

	Level in diet		Daily amount	
Sodium	0.21	%	11.93	g/day
Chloride	0.17	%	9.55	g/day
Magnesium	0.06	%	3.58	g/day
Potassium	0.21	%	11.9	g/day
Copper	21	mg/kg	119	mg/day
Iodine	0.15	mg/kg	0.84	mg/day
Iron	86	mg/kg	477	mg/day
Manganese	27	mg/kg	149	mg/day
Selenium	0.16	mg/kg	895	μg/day
Zinc	107	mg/kg	597	mg/day
Vitamin A	2139	IU/kg	11932	IU/day
Vitamin D	856	IU/kg	4773	IU/day
Vitamin E	47	IU/kg	263	IU/day
Vitamin K	0.53	mg/kg	2.98	mg/day
Biotin	0.21	mg/kg	1.19	mg/day
Choline	1.07	g/kg	5.97	g/day
Folacin	1.39	mg/kg	7.76	mg/day
Niacin, available	10.7	mg/kg	60	mg/day
Pantothenic acid	12.8	mg/kg	71.6	mg/day
Riboflavin	4.0	mg/kg	22.4	mg/day
Thiamin	1.1	mg/kg	6.0	mg/day
Vitamin B_6	1.1	mg/kg	6.0	mg/day
Vitamin B_{12}	16	μg/kg	89.5	μg/day
Linoleic acid	0.11	%	6.0	g/day

FIGURE A-5b Results for the lactating sow model.

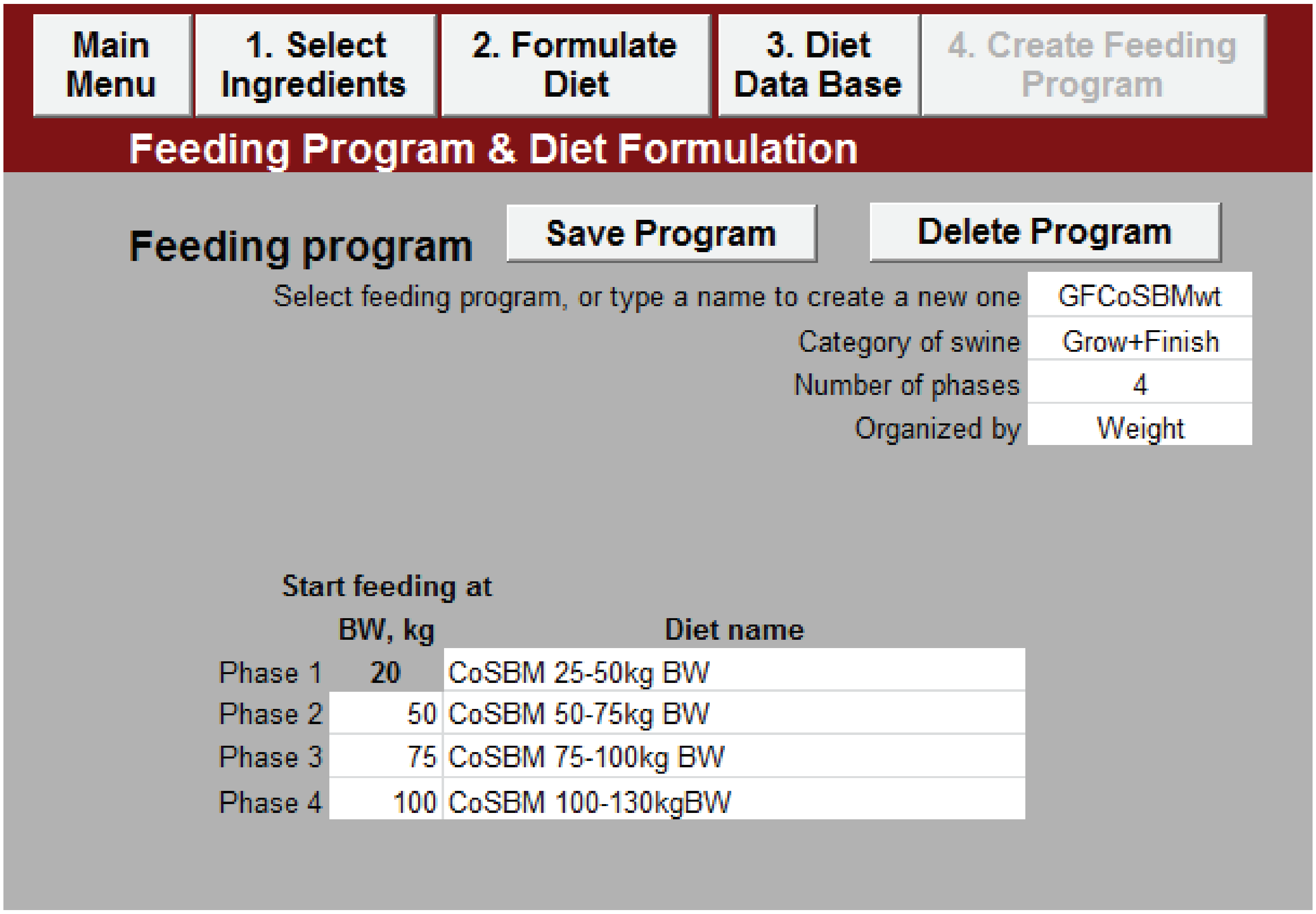

FIGURE A-6 Feeding program and diet formulation.

Appendix B

Committee Statement of Task

A committee will prepare a report that reviews the scientific literature on the nutrition of swine and provides an updated listing of energy and nutrient requirements. All life phases and types of production will be addressed. New recommendations, especially for amino acids, will be made with appropriate consideration of the increased potential for lean gain of modern genotypes of swine. New knowledge about energy utilization by swine, including net energy systems and values, will be added. Information about feed ingredients from the biofuels industry and other new ingredients (e.g., novel soybean products) will be included. Requirements for digestible phosphorus and concentrations of digestible phosphorus in feed ingredients will be updated. A review of the effects of feed additives routinely used in swine diets (e.g., antibiotic growth promoters, enzymes, acidifiers, and beta-agonists) will be included. Effects of feed processing (e.g., pelleting, extrusion, and reduced particle size) on the utilization of feed by different categories of swine will be addressed. Strategies to increase nutrient retention and thus reduce fecal and urinary excretions that could contribute to environmental pollution will be reviewed. Depending on the extent of information available, an update of the current computer model to calculate nutrient requirements may be developed. Tables of feed composition will be expanded with relevant new information. Future areas of needed research will be identified.

Appendix C

Abbreviations and Acronyms

AA	Amino acid
AA_{diet}	Amino acid concentration in the diet dry matter
$AA_{digesta}$	Amino acid concentration in the ileal digesta
AAFCO	Association of American Feed Control Officials
ADF	Acid detergent fiber
ADFI	Average daily feed intake
ADG	Average daily gain
AFIA	American Feed Industry Association
AFSS	Animal Feed Safety System
AID	Apparent ileal digestible
Ala	Alanine
AOAC	Association of Official Analytical Chemists
AOM	Active oxygen method
APHIS	Animal and Plant Health Inspection Service
ARA	Arachidonic acid
ARC	Agricultural Research Council
Arg	Arginine
ASABE	American Society of Agricultural and Biological Engineers
Asp	Aspartic acid
ATTD	Apparent total tract digestibility
AV	Anisidine value
BHA	Butylated hydroxyanisole
BHT	Butylated hydroxytoluene
BL	Whole-body lipid mass
BP	Whole-body protein mass
BSAS	British Society of Animal Science
BSE	Bovine spongiform encephalopathy
BV	Benzidine value
BW	Body weight
cal	Calorie
CAST	Council for Agricultural Science and Technology
CDS	Condensed distillers solubles
CF	Crude fiber
CFR	Code of Federal Regulations
CLA	Conjugated linoleic acid
CP	Crude protein

CVB	Dutch PDV (Product Board Animal Feed)
CWD	Chronic wasting disease
Cys	Cystine
d	Days
Da	Dalton
DADF	Digestible acid detergent fiber
DCP	Digestible crude protein
DDE	Dichlorodiphenyldichloroethylene
DDG	Distillers dried grains
DDGS	Distillers dried grains with solubles
DDT	Dichlorodiphenyltrichloroethane
DE	Digestible energy
DEE	Digestible ether extract
DHA	Docosahexaenoic acid
DM	Dry matter
DMI	Dry matter intake
DNA	Deoxyribonucleic acid
DNSP	Digestible nonstarch polysaccharide
DOM	Digestible organic matter
DON	Deoxynivalenol
DP	Digestible protein
DRES	Digestible residue
EAP	Estimated available phosphorus
EBW	Empty body weight
EDTA	Ethylenediamine tetraacetic acid
EE	Ether extract
EFA	Essential fatty acids
EPA	Eicosapentaenoic acid
EPL	Endogenous phosphorus losses
Eq	Equation
EU	European Union
FAD	Flavin adenine dinucleotide
FAME	Fatty acid methyl esters
FAO	Food and Agriculture Organization of the United Nations
FCH	Fermentable carbohydrate
FDA	Food and Drug Administration
FFA	Free fatty acid
FH_4	Tetrahydrofolic acid
FHP	Fasting heat production
FMN	Flavin mononucleotide
FSIS	Food Safety and Inspection Service
FTU	Phytase activity unit
G:F	Feed efficiency
GC	Gas chromatography
GE	Gross energy
GfE	Society of Nutrition Physiology
GIT	Gastrointestinal tract
Glu	Glutamic acid
Gly	Glycine
GM	Genetically modified
GnRH	Gonadotropin-releasing hormone

H_cE	Heat production associated with body temperature maintenance
HCH	Hexachlorocyclohexane
H_dE	Heat of digestion and assimilation
HE	Heat production
H_eE	Heat production at maintenance
H_fE	Heat of fermentation
H_iE	Heat increment energy
His	Histidine
H_jE	Heat production associated with activity
HP-DDG	High-protein distillers dried grains
HP-DDGS	High-protein distillers dried grains with solubles
HPLC	High-performance liquid chromatography
H_rE	Heat of tissue formation
HSCAS	Hydrated sodium calcium aluminosilicates
H_wE	Heat of waste formation
IFN	International Feed Number
Ig	Immunoglobulin
IgA	Immunoglobulin A
IgG	Immunoglobulin G
Ile	Isoleucine
IOM	Institute of Medicine
IPCC	Intergovernmental Panel on Climate Change
IU	International units
IV	Iodine value
IVGTT	Intravenous glucose tolerance tests
IVICT	Intravenous insulin challenge tests
IVP	Iodine value product
J	Joule
k_f	Partial efficiency of metabolizable energy use for lipid energy gain
k_m	Partial efficiency conversion of metabolizable energy to milk energy
k_{mr}	Partial efficiency of using body tissue(s) to support the energy needs of milk
k_p	Partial efficiency of metabolizable energy use for protein
k_r	Protein and lipid mobilized to support the developing fetus and tissues
LA	Linoleic acid
LCT	Lower critical temperature
Ld	Lipid deposition
L_{diet}	Lipid concentration in the diet dry matter
LEG	Metabolizable energy use for lipid energy gain
Leu	Leucine
LN	Linolenic acid
LS, ls	Expected litter size or number of pigs per litter
Lys	Lysine
$Marker_{diet}$	Indigestible marker in the diet
$Marker_{digesta}$	Indigestible marker in the digesta
MDH	Minnesota Department of Health
ME	Metabolizable energy
MEI	Metabolizable energy intake
MEIR	Reduction in metabolizable energy intake
ME_m	Metabolizable energy for maintenance

Met	Methionine
MMA	Mastitis-metritis-agalactia
MPB	Menadione dimethlypyrimidinol bisulfite
mRNA	Messenger ribonucleic acid
MSB	Menadione sodium bisulfite
MSBC	Menadione sodium bisulfite complex
MUFA	Monounsaturated fatty acid
NAD	Nicotinamide adenine dinucleotide
NADP	Nicotinamide adenine dinucleotide phosphate
NAS	National Academy of Sciences
ND	Not determined
NDF	Neutral detergent fiber
NDL	Nutrient Data Laboratory
NDSC	Neutral detergent soluble carbohydrates
NE	Net energy
NE_m	Net energy for maintenance
NE_p	Net energy for production
NFC	Nonfiber carbohydrates
NPB	National Pork Board
NPPC	National Pork Producers Council
NRC	National Research Council
NSC	Nonstructural carbohydrates
OSI	Oxidative stability index
PABA	Paraaminobenzoic acid
par	parity
PCBs	Polychlorinated biphenyls
Pd	Protein deposition
Pd_{max}	Maximal protein deposition rate
PEG	Metabolizable energy use for protein
PG	Propyl gallate
Phe	Phenylalanine
P_{intake}	Daily phosphorus input
P_{output}	Daily fecal output of phosphorus
ppb	Parts per billion
ppm	Parts per million
Pro	Proline
PUFA	Polyunsaturated fatty acids
PV	Peroxide value
PVPP	Polyvinyl polypyrrolidine
RAC	Ractopamine
RE	Retinol equivalent
SDF	Soluble dietary fiber
Ser	Serine
SFA	Saturated fatty acids
SID	Standardized ileal digestibility
SOD	Superoxide dismutase
STTD	Standardized total tract digestible
t	Time
T	Temperature

TBA	Thiobarbituric acid
TBARS	Thiobarbituric reactive substances
TBHQ	tert-Butylhydroquinone
TDE	Tetrachlorodiphenylethane
TDF	Total dietary fiber
TDS	Total dissolved solids or mineral load
TFWQG	Task Force on Water Quality Guidelines
Thr	Threonine
TID	True ileal digestibility
Trp	Tryptophan
TSE	Transmissible spongiform encephalopathy
Tyr	Tyrosine
U:S	Unsaturated:saturated ratio
UCT	Upper critical temperature
USDA	United States Department of Agriculture
Val	Valine
VFI	Voluntary feed intake
WSC	Water-soluble carbohydrates

Appendix D

Committee Member Biographies

L. Lee Southern *(chair)* holds the Doyle Chambers Distinguished Professorship in the School of Animal Sciences at Louisiana State University (LSU) Agricultural Center. Dr. Southern specializes in nonruminant nutrition; specifically, his research is in the areas of amino acid and mineral utilization by swine and poultry. Dr. Southern has served on the editorial board of *Poultry Science* and the *Professional Animal Scientist* and as associate editor and division editor of the *Journal of Animal Science*. He is currently serving as section editor of *Poultry Science*. He served as a member of the NRC Committee on Animal Nutrition from 1998 to 2002. Dr. Southern has received numerous awards for his professional accomplishments, including the American Feed Industry Association's Nonruminant Nutrition Award from the American Society of Animal Science, the Gamma Sigma Delta Research Award, and the LSU Teaching Merit Honor Role. Dr. Southern received his B.S. and M.S. in animal science from North Carolina State University and his Ph.D. in animal science from the University of Illinois.

Olayiwola Adeola is a professor of animal sciences at Purdue University, where he teaches nonruminant nutrition, emphasizing amino acid nutrition and utilization of plant minerals. Dr. Adeola's research program objective is the development of strategies to enhance production efficiency and promote better health, and sound environmental stewardship. A primary goal of his research is to improve the efficiency of lean meat production and to minimize the flow of potentially detrimental levels of dietary nutrients from animal waste into the environment. Dr. Adeola has served on the editorial board of *Poultry Science*, as associate editor of the *Journal of Animal Science*, and as section editor of the *Canadian Journal of Animal Science*. He is a recipient of the Poultry Nutrition Research Award from the American Feed Industry Association, the Maple Leaf Farms Duck Research Award from the Poultry Science Association, and the American Feed Industry Association's Nonruminant Nutrition Award from the American Society of Animal Science. Dr. Adeola received his B.S. in animal science from the University of Ife, Nigeria, and his M.S. and Ph.D. in animal science from the University of Guelph, Canada.

Cornelis F. M. de Lange is a professor in the Department of Animal Sciences and director of the Livestock Research Program at the University of Guelph in Ontario, Canada. Before his appointment at the University of Guelph, he worked in the commercial feed industry and in applied swine nutrition research. At the University of Guelph, his research aims to support growth of sustainable pork production systems. His specific projects focus on nutrient utilization in growing-finishing pigs, dietary means to reduce the negative impact of pig production on the environment, improving pork meat quality, and enhancing gut health and development in newly weaned piglets. Dr. de Lange is the recipient of the Distinguished Extension Award and the Distinguished Researcher Award, both from the Ontario Agricultural College. Dr. de Lange received his B.Sc. and M.Sc. in animal science from the Agricultural University in Wageningen, The Netherlands, and his Ph.D. in animal nutrition from the University of Alberta, Canada.

Gretchen M. Hill is a professor in the Department of Animal Science at Michigan State University. Her research seeks to increase understanding of the role of trace element nutrition in livestock, from basic nutrient utilization and conservation to the molecular level. She works closely with the feed industry to revise mineral inclusion rates appropriate for today's genetics. Dr. Hill has served on the editorial board of the Journal of Nutritional Biochemistry and as associate editor of the *Journal of Animal Science*. She received the award for Outstanding Advisor in the College of Agriculture and Natural Resources at Michigan State University and the American Feed Industry Association's Nonruminant Nutrition Award from the American Society of Animal Science.

Dr. Hill received her B.S. from the University of Kentucky, M.S. from Purdue University, and Ph.D. in animal nutrition from Michigan State University.

Brian J. Kerr is an animal scientist/lead scientist of the Agricultural Research Service of the U.S. Department of Agriculture's (USDA) Enhanced Animal Production Systems to Increase Natural Resource Utilization and Reduce Environmental Impact Research Unit in Ames, Iowa. Dr. Kerr is responsible for the administrative and scientific functions of a research unit whose mission is focused on reduction of nutrient excretion, emission of malodorous compounds, and release of pathogenic organisms from swine production into the environment. Before his current position, Dr. Kerr was research director at a feed ingredient company and a technical manager at a regional feed company. He has served as associate editor of the *Journal of Animal Science* and on the editorial boards of other publications. Dr. Kerr received his B.S. in animal science and M.S. and Ph.D. in nonruminant nutrition from the University of Illinois.

Merlin D. Lindemann is a professor of swine nutrition and management in the Department of Animal and Food Sciences at the University of Kentucky. Dr. Lindemann's research areas include dietary modifications of nitrogen and phosphorus related to performance and waste management, determination of the feeding value of new byproduct feeds, evaluation of trace minerals for swine, and the effect of supplements on reproductive performance. Dr. Lindemann has served as associate editor of the *Journal of Animal Science* and on the editorial board of the *Professional Animal Scientist*. He received the American Feed Industry Association's Nonruminant Nutrition Award from the American Society of Animal Science and the University of Kentucky George E. Mitchell Jr. Award for Outstanding Faculty Service to Graduate Students. Dr. Lindemann received his B.S. and Ph.D. in animal science from the University of Minnesota.

Phillip S. Miller is a professor of swine nutrition in the Department of Animal Science at the University of Nebraska. Dr. Miller is responsible for conducting swine nutrition research focused on interrelationships among liver metabolism, nutrient intake, and growth criteria in growing-finishing barrows and gilts and research in nutritional energetics and body composition. He has served as associate editor and division editor of the *Journal of Animal Science*. He has won numerous awards for his teaching, including the Gamma Sigma Delta Teaching Award of Merit and the L. K. Crowe Outstanding Undergraduate Advisor Award. Dr. Miller received his B.S., M.S., and Ph.D. in nutrition from the University of California, Davis.

Jack Odle holds the William Neal Reynolds Distinguished Professorship in nutritional biochemistry at North Carolina State University. Dr. Odle's research has focused on neonatal nutrition and metabolism, particularly the developmental aspects of lipid digestion, absorption, and metabolism at the molecular, cellular, and whole-animal levels. His other research interests include effects of dietary carnitine and medium-chain triglycerides on growth and the effects of bioactive peptides and polyunsaturated fatty acids on development of the neonatal intestine. Dr. Odle has served as associate editor of the *Journal of Nutrition* and as an elected counselor of the American Society for Nutrition. He has received the American Feed Industry Association's Nonruminant Nutrition Award from the American Society of Animal Science. Dr. Odle received his B.S. in animal science from Purdue University, M.S. in animal nutrition from the University of Wisconsin, and Ph.D. in nutritional sciences and animal science from the University of Wisconsin.

Hans H. Stein is a professor in the Department of Animal Sciences at the University of Illinois at Urbana-Champaign. His research focuses on the digestion, absorption, and utilization of energy and macronutrients of feed ingredients, as well as digestive physiology, feed ingredient evaluation, and nutrient management. His honors include the Pork Information Partner Award and the Research Award from Gamma Sigma Delta. In 2010, he was the recipient of the American Feed Industry Association's Nonruminant Nutrition Award from the American Society of Animal Science. Dr. Stein serves on several national committees, including the Nonantimicrobials Working Group and the Animal Science Committee, both of the National Pork Board, and as an associate editor of the *Journal of Animal Science*. He received a Green Diploma in agriculture (Farmer's Licence) from the Farmer's Agricultural School in Graasten, Denmark, M.S. in animal science from the Royal Veterinary and Agricultural University in Denmark, and Ph.D. in animal science from the University of Illinois.

Nathalie L. Trottier is an associate professor in the Department of Animal Science at Michigan State University. Her research interests involve amino acid metabolism during growth and lactation, including investigation of mechanisms of amino acid utilization by the gut and the mammary gland. She is the research editor for Michigan State University's *Equine Program Newsletter* and has served on the editorial board of the *Journal of Animal Science*. She is currently serving as the American editor of the nonruminant nutrition section for the international *ANIMAL Journal*. Dr. Trottier received her B.S. in agronomy at McGill University in Canada, M.S. in animal nutrition at McGill University, and Ph.D. in animal nutrition at the University of Illinois.

Appendix E

Recent Publications of the Board on Agriculture and Natural Resources

POLICY AND RESOURCES

Achievements of the National Plant Genome Initiative and New Horizons in Plant Biology (2008)
Achieving Sustainable Global Capacity for Surveillance and Response to Emerging Diseases of Zoonotic Origin: Workshop Report (2008)
Agricultural Biotechnology and the Poor: Proceedings of an International Conference (2000)
Agriculture, Forestry, and Fishing Research at NIOSH (2008)
Agriculture's Role in K-12 Education (1998)
Air Emissions from Animal Feeding Operations: Current Knowledge, Future Needs (2003)
An Evaluation of the Food Safety Requirements of the Federal Purchase Ground Beef Program (2010)
Animal Biotechnology: Science-Based Concerns (2002)
Animal Care and Management at the National Zoo: Final Report (2005)
Animal Care and Management at the National Zoo: Interim Report (2004)
Animal Health at the Crossroads: Preventing, Detecting, and Diagnosing Animal Diseases (2005)
Biological Confinement of Genetically Engineered Organisms (2004)
California Agricultural Research Priorities: Pierce's Disease (2004)
Changes in the Sheep Industry in the United States: Making the Transition from Tradition (2008)
Countering Agricultural Bioterrorism (2003)
Critical Needs for Research in Veterinary Science (2005)
Designing an Agricultural Genome Program (1998)
Diagnosis and Control of Johne's Disease (2003)
Direct and Indirect Human Contributions to Terrestrial Carbon Fluxes (2004)
Ecological Monitoring of Genetically Modified Crops (2001)
Emerging Animal Diseases: Global Markets, Global Safety: Workshop Summary (2002)
Emerging Technologies to Benefit Farmers in Sub-Saharan Africa and South Asia (2008)
Enhancing Food Safety: The Role of the Food and Drug Administration (2010)
Ensuring Safe Food: From Production to Consumption (1998)
Environmental Effects of Transgenic Plants: The Scope and Adequacy of Regulation (2002)
Evaluation of a Site-Specific Risk Assessment for the Department of Homeland Security's Planned National Bio- and Agro-Defense Facility in Manhattan, Kansas (2010)
Exploring a Vision: Integrating Knowledge for Food and Health (2004)
Exploring Horizons for Domestic Animal Genomics (2002)
Frontiers in Agricultural Research: Food, Health, Environment, and Communities (2003)
Future Role of Pesticides for U.S. Agriculture (2000)
Genetically Engineered Organisms, Wildlife, and Habitat: A Workshop Summary (2008)
Genetically Modified Pest-Protected Plants: Science and Regulation (2000)
Global Challenges and Directions for Agricultural Biotechnology (2008)
The Impact of Genetically Engineered Crops on Farm Sustainability in the United States (2010)
Incorporating Science, Economics, and Sociology in Developing Sanitary and Phytosanitary Standards in International Trade (2000)
Letter Report to the Florida Department of Citrus on the Review of Research Proposals on Citrus Greening (2008)
National Capacity in Forestry Research (2002)
The National Plant Genome Initiative (2002)

National Research Initiative: A Vital Competitive Grants Program in Food, Fiber, and Natural-Resources Research (2000)
Predicting Invasions of Nonindigenous Plants and Plant Pests (2002)
Professional Societies and Ecologically Based Pest Management (2000)
The Public Health Effects of Food Deserts: Workshop Summary—joint study with Institute of Medicine (2009)
Publicly Funded Agricultural Research and the Changing Structure of U.S. Agriculture (2002)
Review of the Methodology Proposed by the Food Safety and Inspection Service for Risk-Based Surveillance of In-Commerce Activities: A Letter Report (2009)
Review of the Methodology Proposed by the Food Safety and Inspection Service for Followup Surveillance of In-Commerce Businesses: A Letter Report (2009)
Review of the U.S. Department of Agriculture's Animal and Plant Health Inspection Service Response to Petitions to Reclassify the Light Brown Apple Moth as a Non-Actionable Pest: A Letter Report (2009)
Safety of Genetically Engineered Foods: Approaches to Assessing Unintended Health Effects (2004)
Scientific Advances in Animal Nutrition: Promise for a New Century (2001)
The Scientific Basis for Estimating Emissions from Animal Feeding Operations: Interim Report (2002)
The Scientific Basis for Predicting the Invasive Potential of Nonindigenous Plants and Plant Pests in the United States (2002)
Scientific Criteria to Ensure Safe Food (2003)
Status of Pollinators in North America (2007)
Strategic Planning for the Florida Citrus Industry: Addressing Citrus Greening (2010)
Sustaining Global Surveillance and Response to Emerging Zoonotic Disease (2009)
Toward Sustainable Agricultural Systems in the 21st Century (2010)
Transforming Agricultural Education for a Changing World (2009)
The Use of Drugs in Food Animals: Benefits and Risks (2000)

ANIMAL NUTRITION PROGRAM—NUTRIENT REQUIREMENTS OF DOMESTIC ANIMALS SERIES AND RELATED TITLES

Mineral Tolerance of Animals: Second Revised Edition (2005)
Nutrient Requirements of Beef Cattle, Seventh Revised Edition, Update (2000)
Nutrient Requirements of Dairy Cattle, Seventh Revised Edition (2001)
Nutrient Requirements of Dogs and Cats (2006)
Nutrient Requirements of Fish and Shrimp (2011)
Nutrient Requirements of Horses: Sixth Revised Edition (2007)
Nutrient Requirements of Nonhuman Primates, Second Revised Edition (2002)
Nutrient Requirements of Small Ruminants: Sheep, Goats, Cervids, and New World Camelids (2007)
Nutrient Requirements of Swine, Tenth Revised Edition (1998)
Safety of Dietary Supplements for Horses, Dogs, and Cats (2009)
Scientific Advances in Animal Nutrition: Promise for a New Century (2001)
The First Seventy Years 1928-1998: Committee on Animal Nutrition (1998)
The Scientific Basis for Estimating Emissions from Animal Feeding Operations: Interim Report (2002)

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