Diet Formulation for Swine

The first component of a nutritional program is diet formulation. The key steps on how to formulate diets for swine are discussed in this fact sheet.

1. Set the dietary energy level

The first and most important step in diet formulation is to set the energy concentration. Energy is the most expensive component of the diet and the levels of other nutrients are set relative to the energy concentration of the diet. Incremental changes in dietary energy have direct impact on important production indicators, such as diet cost, growth performance, and carcass criteria.

The energy level used in formulation should be based on an in-depth analysis to determine the most economical level considering the value of incremental changes in energy on production indicators (**Figure 1**) and market price. A production tool that incorporates the impact of dietary energy on growth rate, feed efficiency, and carcass yield has been developed to aid in determining the optimum dietary energy level in the grow-finish phase (Net Energy Model).

2. Determine the standardized ileal digestible (SID) lysine:calorie ratio

Once the dietary energy level is determined, the lysine:calorie ratio is set. The lysine requirement should be expressed as a ratio to energy instead of a dietary lysine percentage because changes in dietary energy density affect feed intake and/or growth rate. Thus, the lysine to calorie ratio is used to ensure the right amount of lysine is provided in diets that vary in energy density.

The lysine levels used in formulation should be based on lysine requirement estimates. The lysine requirements are determined by different methods that are preferentially selected based on the accuracy of requirement estimates, feasibility of implementation, and level of investment. The lysine requirements can be estimated from research data conducted at universities (**Figure 2**), genetic suppliers, or feed companies; from research conducted within the production system; from protein accretion curves; or from growth rate and feed intake data.

3. Determine the ratio of other amino acids relative to lysine

Once the lysine:calorie ratio is determined, the levels of other amino acids are set based on a ratio to lysine. Amino acid ratio is a means of expressing the requirements for amino acids relative to the requirement for lysine. Lysine is used as a reference because it is typically the first-limiting amino acid in most swine diets and the proper concentration of lysine and other amino acids is essential for protein synthesis. The amino acid ratios are often utilized because the requirements for amino acids remain relatively constant relative to lysine for a given stage of growth. In diet formulation, the use of amino acid to lysine ratios makes establishing the levels for other amino acids relatively easy.

The amino acid levels used in formulation should be based on requirement estimates. The requirements of amino acids relative to lysine can be depicted as a diminishing returns model. This model can be used to determine which ratio provides 95 to 99% of the maximum performance and indicates the most economical amino acid ratio. Thus, the optimum amino acid ratio should be set by balancing the value accrued in performance to the incremental cost to increase the ratio.

4. Determine the standardized total tract digestible (STTD) phosphorus and calcium:phosphorus ratio

The dietary phosphorus level should be based on requirement estimates to provide adequate phosphorus levels for performance, but taking into consideration the diet cost and environmental concerns. Phosphorus is essential for growth and development, but excess supplementation can lead to unnecessary expenses and increased phosphorus excretion.

The dietary calcium levels are set relative to phosphorus in a calcium:phosphorus ratio. The ratio of calcium to phosphorus is important because of the close association of both minerals. The dietary concentration of calcium affects the absorption and retention of phosphorus, particularly in diets with excess calcium and marginal phosphorus. Diets with excess calcium are not uncommon in swine diets because, unlike phosphorus, there is no economic and environmental concerns regarding dietary calcium. Using calcium:phosphorus ratio to set calcium levels is important to avoid an imbalance between the minerals, which is particularly important in diets with marginal levels of phosphorus.

5. Set levels of vitamins, minerals, and other ingredients

Finally, the levels of vitamins, minerals and any other ingredients are set in the diet formulation. Recommendations for trace minerals and vitamins levels are available at KSU Premix & Diet Recommendations.

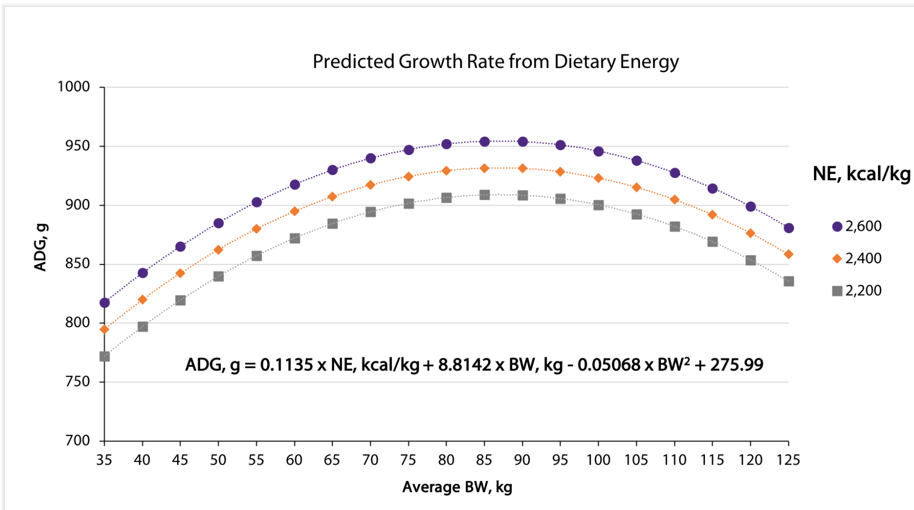

Figure 1. Equation to predict growth rate of grow-finish pigs fed varying energy levels. Every ±100 kcal NE/kg in dietary energy represents ±11.35 g or ±0.025 lb in average daily gain (Nitikanchana et al., 2015 doi:10.2527/jas.2015-9005).

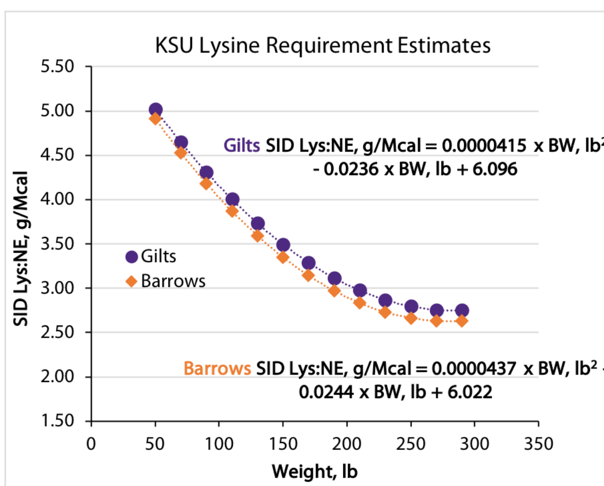

Figure 2. KSU lysine recommendations for grow-finish pigs (KSU Lysine Recommendations).

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Swine Nutrient Requirements

Nutritional requirements are defined as the amount of nutrients that pigs require to meet the needs for maintenance, growth, production, reproduction, and other functions. Generally, pigs require six classes of nutrients: carbohydrates, proteins, fats, minerals, vitamins, and water.

In animal populations and particularly in swine production, it is essential to distinguish between requirements and recommendations:

- **Nutritional requirements**: are determined for individual animals.
- **Nutritional recommendations**: are given for a population of animals.

Recommendations are often determined as the requirement of an average animal in the population. However, nutrient requirements vary between animals and the recommendations may not meet the requirement of a certain percentage of the population. Thus, recommendations often have a wider margin to take into account the variation in needs within a population.

Factors affecting nutrient requirements

Nutrient requirements are influenced by a combination of performance potential and feed intake. The nutrient concentration in the diet is adjusted according to feed intake to meet the requirements during each stage of production. Providing diets with nutrient levels below the requirements results in suboptimal performance, whereas feeding nutrients above the requirements increases feed cost and nutrient excretion. Thus, in order to ensure optimal production at an economical cost, it is important to understand the factors involved in nutrient requirement estimates and adjust the diet formulation accordingly.

Several factors affect the estimation of nutrient requirements in pigs. In fact, any factor that influences performance and feed intake is likely to affect nutrient requirements estimates. Generally, improvements in growth performance or productivity and decreases in feed intake are associated with increased demand for nutrient fortification in the diet to meet the requirements. Some of the most important factors are:

- Genetics and gender
- Dietary energy concentration
- Environmental temperature
- Health status
- Stocking density
- Feeding strategy and degree of competition for feed
- Variability of nutrient content and availability in ingredients
- Presence of molds, toxins, or anti-nutritional factors in the diet
- Inclusion of growth promoters or feed additives in the diet

Methods to estimate nutrient requirements

The most common approaches to estimate nutrient requirements are the factorial and empirical methods (Hauschild et al., 2010).

Factorial method

The nutrient requirements are obtained by combining the estimated requirements for maintenance and production. The factorial method uses a modeling approach from an average individual in the population and the requirements derive from equations that are usually a function of body weight and production parameters. Using this approach, the limitation lies on determining which animal should be used to estimate the requirements. For example, if the factorial requirement estimates for the average pig are applied to the population, because of natural between-animal variation approximately 50% of the population will not receive enough nutrients to express full growth potential. This method was used by the National Research Council to develop most of the recommendations published on the latest NRC (2012).

Empirical method

In the empirical method, dose-response or titration studies are conducted to determine the nutrient requirements. Dose-response studies are becoming increasingly popular to determine nutrient requirements because the estimates better represent the requirements of the population. The limitation of the empirical method lies on the application of requirement estimates to other populations or beyond the range of body weight.

In dose-response studies, different nutrient levels are tested. It is important to allocate most of the levels around an expected requirement and to include one level sufficiently high to produce the maximum response as well as one level sufficiently low to induce deficiency (**Figure 1**). The level associated with the best performance is determined through statistical analysis, which is crucial to accurately determine the nutrient requirement. Means comparisons are not an adequate method to analyze data from dose-response studies because it does not take into account the structure of treatment levels. Rather, modelling a response curve using linear and non-linear models is the most appropriate approach to determine a nutritional requirement. The response curve adapts to the shape of the data and indicates the nutrient level that maximizes or minimizes a performance criterion.

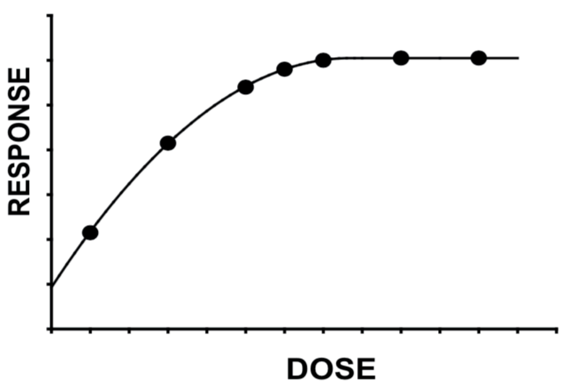

Figure 1. Distribution of nutrient levels in dose-response studies (Simongiovanni et al., 2012).

Estimating nutrient requirements

Nutrient requirements are often estimated under different conditions. The approach to estimate nutrient requirements is similar, but some particularities of amino acids, calcium, and phosphorus are detailed here.

Determining lysine requirements

The lysine requirements (**Table 1**) can be estimated by different methods that are preferentially selected based on the accuracy of requirement estimates, feasibility of implementation, and level of investment.

♦ From research data

Lysine requirements can be adapted from published research data from universities (**Figure 2**, KSU Lysine Recommendations), genetic suppliers, or feed companies. The lysine recommendations provided from research are usually derived from dose-response experiments and are often the best data available. But it is important to take into consideration the genetic line, level of growth rate and feed intake, health status, and housing conditions adopted in the experiment before applying the recommendations to a production system.

♦ From research within the production system

Lysine requirements can be derived from dose-response experiments conducted in research facilities within the production system. The lysine recommendations are most accurately determined by using this method because it better reflects the production system conditions. But it also requires more investment in research facilities and personnel expertise to conduct experiments.

♦ From protein accretion curves

Lysine requirements can be determined from curves of protein accretion derived from weights and ultrasound measurements of pigs within a production system (Smith et al., 1999). This method provides good estimates of farm-specific lysine recommendations because it reflects the conditions found in a commercial production system. The weighing and ultrasound scanning start earlier in the grower period and are collected past the normal market weights to ensure the lysine requirements at the beginning and end of the period are accurately estimated. Although this method is conducted under commercial facilities within the production system and does not require investment in research facilities, an ultrasound and a skilled technician are required to conduct the measurements and perform the modeling with precision.

♦ From growth rate and feed intake data

Lysine requirements can be estimated using growth rate and feed intake data. A simple rule of thumb is that grow-finish pigs require approximately 20 g of standardized ileal digestible (SID) lysine per kg of daily gain or 9 g per lb of daily gain (Main et al., 2008). Considering the growth rate and the feed intake of pigs in the production system, the lysine recommendations can be estimated to provide 20 g of SID lysine per kg of daily gain in diet formulation. This method is not as precise, but it provides a reasonable estimate of the lysine requirement.

Determining other amino acid requirements

The amino acid requirements are usually estimated by dose-response studies and the most common approach is to express the requirements as an amino acid ratio (**Table 1**). Amino acid ratio is a means of expressing the requirements for amino acids relative to the requirement for lysine. Lysine is used as a reference because it is typically the first-limiting amino acid in most swine diets and the proper concentration of lysine and other amino acids is essential for protein synthesis.

In dose-response experiments, the first limiting amino acid in the diet must be the amino acid for which the requirement is being estimated and the second limiting amino acid must be lysine. The supply of other amino acids and nutrients should meet or slightly exceed the requirements to avoid being a limiting factor. Using this approach, the requirement is determined at the point which both the tested amino acid and lysine are equally limiting and can, therefore, be expressed relative to lysine (Simongiovanni et al., 2012).

The requirements of amino acids relative to lysine can be often depicted as a diminishing returns model. This model can be used to determine which ratio provides 95 to 99% of the maximum performance and indicates the most economical amino acid ratio. Thus, the optimum amino acid ratio should be set by balancing the value accrued in performance to the incremental cost to increase the ratio.

Determining calcium or phosphorus requirements

The requirements of calcium or phosphorus are usually estimated by dose-response studies (**Table 2**). The estimation of requirements needs to take into consideration the calcium and phosphorus concentrations as well as the calcium:phosphorus ratio because of the close association between the minerals. Typically, wide calcium:phosphorus ratios or excessive calcium and marginal phosphorus concentration interfere with phosphorus absorption.

Table 1. Minimum standardized ileal digestible lysine and amino acid to lysine ratio for growing pigs and sows

	Growing pigs weight range, lb						Sows[4]	
SID amino acids[1]	15 to 25	25 to 55	55 to 130	130 to 175	175 to 220	220 to 285	Gestating	Lactating
Lysine, %[2]	1.35	1.25	1.08	0.88	0.78	0.70	0.60	1.05
Amino acid to lysine ratio, %[3]								
Methionine	28	28	28	28	28	28	28-29	28-29
Methionine + Cysteine	56	56	56	56	57	58	68-70	53-54
Threonine	62	62	62	62	63	64	74-76	63-64
Tryptophan	19	19	18	18	18	18	19-21	19-21
Isoleucine	52	52	52	52	52	52	58	56
Valine	67	67	68	68	68	68	71-76	64-70

[1]Minimum levels based on the NRC (2012) ingredient loading values.
[2]Minimum lysine levels considering a diet with 1,150 kcal NE/lb for growing pigs, 1,130 kcal NE/lb for gestating sows, and 1,160 kcal NE/lb for lactating sows.
[3]Minimum ratios to achieve approximately 95% of maximum growth performance. Minimum ratios of threonine, tryptophan, isoleucine, and valine can be greater depending on diet formulation.
[4]Data on amino acid requirements for contemporary sows is limited.

Table 2. Minimum calcium and phosphorus dietary levels for growing pigs and sows								
	Growing pigs weight range, lb							Sows[2]	
	12 to 15	15 to 25	25 to 50	50 to 130	130 to 175	175 to 220	220 to 285	Gestating	Lactating
Total calcium, %[1]	0.85	0.80	0.70	0.66	0.59	0.52	0.46	0.80	0.80
STTD phosphorus, %[1]	0.63	0.56	0.43	0.38	0.33	0.29	0.26	0.50	0.50

[1]Minimum levels based on the NRC (2012) ingredient loading values.
[2]Data on calcium and phosphorus requirements for contemporary sows is limited.

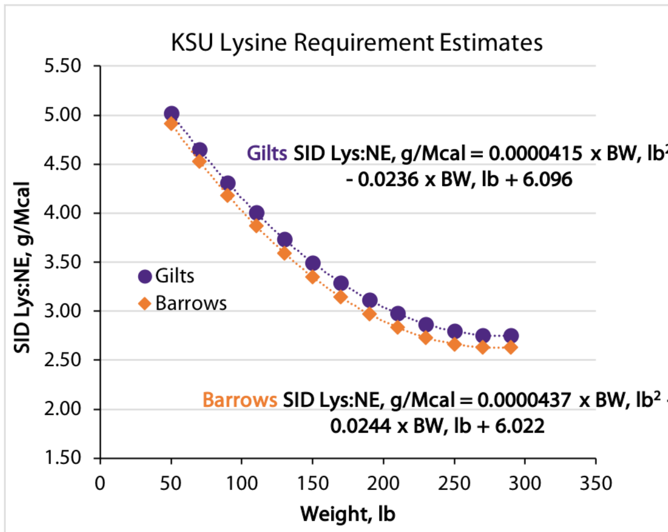

Figure 2. KSU lysine recommendations for grow-finish pigs (KSU Lysine Recommendations).

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Energy Sources for Swine Diets

Cereal Grains and Co-Products

The main energy sources for swine are the cereal grains corn, milo, wheat, barley, and their co-products. In cereal grains, starch and oil are positively correlated with energy values, whereas fiber is negatively correlated. The most common cereal grains and co-products used in swine diets are discussed in this fact sheet.

Selection of energy sources

The decision of selecting an energy source for swine diets must consider nutritional, economic, and logistic determinants, including: digestibility of energy and nutrients, variability in nutrient concentration, ability to consistently source a high-quality ingredient, availability of bin space in the feed mill, grinding capabilities, handling characteristics, cost, and production goals. **Table 1** presents the typical use of energy sources in swine diets considering some limiting factors.

Relative feeding value is often used to compare the value of a particular feed ingredient to the value of a standard energy source, typically corn. The relative feeding value considers the energy content and nutrient levels to evaluate the energy source.

Dietary energy formulation

There are two primary means to select ingredients when formulating the energy concentration in swine diets: allowing dietary energy to change as the ingredient is added or keeping dietary energy constant.

Formulating to allow dietary energy to change

Using this formulation method, dietary energy fluctuates as the energy source is included in the diet. In this case, a low energy ingredient decreases dietary energy and is often associated with lower growth rate and poorer feed efficiency. Cost of additional finishing space to achieve the same market weight or loss in revenue from lighter carcass weight must also be considered. The use of this formulation method is economically justifiable if the negative impact on pig value by lowering dietary energy is offset by savings in feed cost or improvements in income over feed cost.

Formulating to a constant dietary energy

Using this formulation method, dietary energy is kept constant as the energy source is included in the diet. In this case, a low energy ingredient is usually combined with a fat source or other high energy ingredient to maintain the same base energy concentration in the diet. The use of this formulation method typically maintains similar growth rate and feed efficiency. Thus, feed cost is an accurate estimate of ingredient value.

Cereal grains

Cereal grains typically provide most of the energy in swine diets. Usually, cereal grains have a relatively high concentration of starch, good palatability, and high digestibility. Corn is the leading cereal used in the United States and many pork producing countries. Corn contains a greater energy density than other cereal grains and is usually the standard to which other cereal grains are compared.

Corn

Corn is the most common cereal grain used in swine diets in the United States and many countries around the world. Corn contains relatively greater energy level than other cereal grains due to its high concentration of starch and oil, and low concentration of fiber.

Corn contains approximately 60 to 65% starch (NRC, 2012) with apparent total tract digestibility of around 90 to 96% (Rojas and Stein, 2015). Oil content is around 3.5% and fiber content is less than 10% NDF (NRC, 2012). These characteristics make the energy value of corn relatively greater than other cereal grains.

Crude protein (7 to 9%) and lysine content (0.25%) in corn is less than most other cereal grains (NRC, 2012), but standardized ileal digestibility of amino acids is relatively high, around 75 to 85% (Cervantes-Pahm et al., 2014). Phosphorus content in corn is approximately 0.25%, but standardized total tract digestibility of phosphorus is only 25 to 30% because at least 2/3 of the phosphorus is bound to phytate. The addition of exogenous phytase is a common practice in corn-based diets to increase phosphorus digestibility to around 45 to 60% (Almeida and Stein, 2012).

Improvements in genetic selection and modification have resulted in some corn varieties with enhanced nutrient profiles for use in swine diets. These corn varieties include nutrient dense, high oil, high lysine, and low phytate corn. However, the market availability of these corn varieties is typically limited.

Milo or Sorghum

Milo or sorghum is grown for human consumption, livestock feeding, and ethanol production in many countries around the world. Milo is an excellent energy source and can replace all or part of the corn in swine diets (Stein et al., 2016).

The concentration of starch and fiber in milo is very similar to that in corn, but milo contains slightly less oil than corn which results in an energy content of 98 to 99% relative to that of corn (Goodband et al., 2016). Because of this, pigs fed milo-based diets generally have similar growth rate but slightly poorer feed efficiency as those fed corn-based diets. A strategy that can improve feed efficiency and relative feeding value of milo to corn is fine grinding (Paulk et al., 2015).

Crude protein (9%) and lysine content (0.20%) are similar to corn (NRC, 2012). The concentration of some other amino acids, particularly threonine, tryptophan, and valine, is greater in milo compared to corn (Goodband et al., 2016), but standardized ileal digestibility of amino acids is slightly lower in milo than corn, around 70 to 75% (Cervantes-Pahm et al., 2014). The use of feed-grade amino acids allows to balance for amino acids while lowering the amount of soybean meal or other protein sources in milo-based diets. While generally not a concern in milo grown in the United States, the presence of tannins in milo must be considered, as tannins in concentrations greater than 1% negatively affect digestibility of amino acids (Stein et al., 2016).

Milo contains more saturated fatty acids and less polyunsaturated fatty acids than corn (Goodband et al., 2016). This characteristic may improve pork fat quality and decrease carcass iodine value and might allow for greater inclusion of co-products high in polyunsaturated fatty acids, such as distillers dried grains with solubles, compared to corn-based diets.

Wheat

Wheat is the traditional source of energy in swine diets in Canada, Europe, and Australia. Wheat is an excellent feed grain for swine, but usually is not competitively priced with corn in the United States. Wheat can replace all or part of the corn in swine diets without affecting growth performance (Stein et al., 2016).

The concentration of starch and fiber in wheat is similar to that in corn, but wheat contains significantly less oil (1.8%) than corn (NRC, 2012) which results in an energy content of 91 to 97% relative to that of corn (Stein et al., 2010).

Crude protein (14%) and amino acid content, particularly lysine (0.40%), threonine, and tryptophan, are greater in wheat than in corn (NRC, 2012; Rosenfelder et al., 2013). The standardized ileal digestibility of amino acids is relatively high and similar to that in corn, around 75 to 85% (Cervantes-Pahm et al., 2014). These characteristics reduce the amount of soybean meal or other protein sources and feed-grade amino acids in wheat-based diets. Phosphorus concentration and availability in wheat is greater than in corn due to the presence of endogenous phytase that improves phosphorus digestibility (Rosenfelder et al., 2013).

Based on the greater concentration of amino acids and phosphorus, wheat is generally given a relative feeding value greater than that of corn (approximately 105 to 110% of corn), but the energy content of wheat needs to be accounted for in wheat-based diets.

Wheat tends to flour when finely ground, which may reduce feed intake and increase the risk on gastric lesions. Thus, wheat should be coarsely ground to an average particle size of 600 μm (Stein et al., 2010).

Barley

Barley is grown mainly for malting or livestock feeding in the United States, Canada, Europe, and Australia. The nutrient composition varies among hulled and dehulled barley grains.

Barley contains lower concentration of starch (50%) and oil (2%) and greater concentration of fiber (18% NDF) compared to corn (NRC, 2012), which results in lower relative feeding value than that of corn (approximately 90 to 95% of corn) (Stein et al., 2016). However, there is significant variability in fiber concentration in barley varieties and, therefore, the replacement of corn by barley may not reduce growth performance under all circumstances (Woyengo et al., 2014).

Barley fiber is more fermentable than fiber from corn. The greater content of soluble fiber in barley increases hindgut fermentation and may improve gut health, but may also reduce feed intake and feces consistency in pigs (Wang et al., 2018).

Crude protein (11%) and lysine content (0.40%) are greater in barley than in corn (NRC, 2012), and standardized ileal digestibility of amino acids is similar to that in corn, around 75 to 85% (Cervantes-Pahm et al., 2014).

Oats

Oats is mainly grown for human consumption and only smaller quantities are used for livestock feeding.

Oats contains lower concentration of starch (39%) and greater concentration of oil (5%) compared to corn (NRC, 2012). The concentration of fiber (25% NDF) in oats is greater than that of corn or any other cereal grain (NRC, 2012).

Crude protein (11%) and lysine content (0.5%) are greater in oats than in corn. Oat protein contains a favorable amino acid profile and greater standardized amino acid digestibility compared to corn or any other cereal grain, around 80 to 90% (Cervantes-Pahm et al., 2014).

Although the amino acid profile is favorable, the high fiber content limits the application of oats in swine diets (Stein et al., 2016). Oats are most commonly included in initial nursery diets because the greater content of insoluble fiber may improve gut health and reduce post-weaning diarrhea in weanling pigs. Oats may also be included in gestation diets for sows.

Cereal grain co-products

Cereal grains are processed into products for human consumption or industrial application and the resulting co-products are used in livestock feeding. Cereal co-products tend to be more variable in nutrient concentration and digestibility and, therefore, their inclusion in swine diets may be limited. Distillers dried grains with solubles (DDGS) is commonly used in swine diets and is the primary co-product of ethanol production from corn, milo, or wheat. Corn co-products from the corn milling industry include corn gluten feed, corn gluten meal, and corn hominy feed. Wheat co-products are also included in swine diets and derived from the wheat milling industry.

Distillers dried grains with solubles (DDGS)

Corn DDGS is extensively used to partially replace corn in swine diets in the United States. Distillers dried grains with solubles is a co-product of fermentation during ethanol production, which results in removal of most of the starch in corn. As corn composition is approximately 2/3 starch and 1/3 other nutrients, it is generally assumed that the other nutrients are concentrated by approximately 3 times in DDGS compared to corn (Stein et al., 2016). The fermentation process also releases a large proportion of phosphorus bound to phytate, which greatly increases the digestibility of phosphorus in DDGS (Almeida and Stein, 2012). In contrast, the fermentation and drying processes negatively affect digestibility of most amino acids, particularly lysine (Kim et al., 2012). Also, if originally present in corn, mycotoxins are unaffected by the fermentation and drying processes and are concentrated in DDGS.

Corn DDGS contain similar concentration of metabolizable energy than corn, but net energy is variable. The concentration of oil may vary from less than 5% to more than 10% depending on the degree of oil recovery during processing. Production tools were developed to aid in determining the energy value of DDGS sources (KSU Energy Value of DDGS, **Figure 1**) and the economic dietary DDGS level in the grow-finish phase (DDGS Calculator).

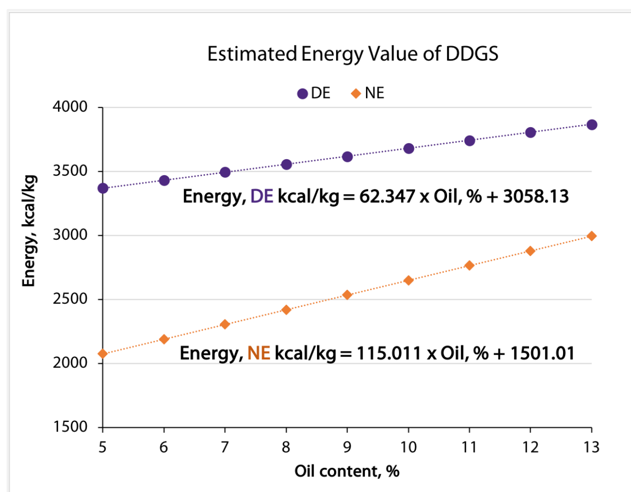

Figure 1. Equations to predict digestible (DE) and net energy (NE) values of DDGS varying in oil content. Every ±1% in oil content represents ±115 kcal/kg or ±52 kcal/lb of NE (KSU Energy Value of DDGS, Graham et al., 2014 doi:10.2527/jas.2014-7678).

Corn DDGS is rich in polyunsaturated fatty acids, which negatively affects pork fat quality and increases carcass iodine value. Carcass yield is also negatively influenced by the addition of DDGS in diets because of the high fiber content that increases gut fill and visceral weight. Adoption of a withdrawal strategy for DDGS prior to marketing is important to reduce the impact on iodine value and restore carcass yield (Asmus et al., 2014; Lerner et al., 2018).

Corn co-products

Corn co-products derived from the wet milling industry include corn gluten feed and corn gluten meal, whereas corn hominy feed is a corn co-product from the dry milling industry. The milling processes fractionate corn into its components to produce a variety of food products while the product streams are utilized in feeds.

Corn gluten feed is derived from the wet milling industry and contains many product streams from the milling process. Because of that, the composition of corn gluten feed is typically more variable than that of other corn co-products (Stein et al., 2016). Corn gluten feed contains very low concentration of starch and high fiber content, which results in lower energy value compared to corn (NRC, 2012).

Corn gluten meal is also derived from the wet milling industry and is considered a high protein co-product, containing around 60% crude protein (NRC, 2012). However, the amino acid profile in any corn co-product is similar to that of corn, which is not the ideal profile for swine (Almeida et al., 2011). Corn gluten meal is considered as a partial corn replacement due to its lower fiber content compared to other corn co-products (NRC, 2012).

Corn hominy feed is derived from the dry milling industry and contains a combination of corn bran, germ, and starch. Corn hominy feed is the corn co-product with the most similar composition to that of corn (NRC, 2012). The concentration of starch and oil is greater than any other corn co-product (NRC, 2012). Corn hominy feed is, therefore, considered suitable for use as a partial corn replacement in swine diets (Stein et al., 2016).

Wheat co-products

Co-products from the wheat flour industry are collectively known as wheat middlings, but sometimes are divided according to protein and fiber concentrations into wheat bran, wheat shorts, wheat red dog, and wheat mill run. The wheat milling process removes the starch from wheat, which results in co-products with lower energy density and higher protein and fiber content (Rosenfelder et al., 2013). The concentration of total fiber is usually between 25 and 35%, which may reduce growth performance and carcass yield with high inclusion of wheat middlings. Wheat middlings is often used as a fiber source in diets for gestating sows.

The low bulk density of wheat middlings increases the volume of the feed unless is in a pelleted form. Capacity of mixers, trucks, feed bins, and feeders must be considered when adding unpelleted wheat middlings or other ingredients with low bulk density to the diet, particularly at relatively high inclusion rates.

Co-products from food and pet food industries

Co-products from the food and pet food industries have an appealing nutrient profile and cost-effectiveness to be incorporated into swine diets. Bakery meal and pet food rations are the most common co-products available for use in swine diets. The main challenge lies on managing the variability in nutrient composition and the often high levels of salt, fat, and sugar in the products (Liu et al., 2018). Variability can be reduced by single-sourcing from one factory and making separate batches for each co-product. Even so, co-products should be regularly sampled and analyzed to maintain up-to-date nutrient values for use in diet formulation.

The nutrient values should be incorporated with caution into the diet formulator considering there is an analytical variability in addition to the variation in ingredient composition. In that sense, allowing a margin of safety for nutrient values is advisable. Also, the variability can be managed by adopting a conservative approach in diet formulation and setting the amino acids and phosphorus levels slightly above the estimated requirements.

Composition of food ingredients found in the USDA Food Composition Databases website can be used for a reference to estimate nutrient values.

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Table 1. Inclusion rates and limitations of common energy sources in swine diets

Ingredient	Swine diet[1] Nursery < 25 lb	Nursery > 25 lb	Grow-finish	Gestation	Lactation	Limitation
Alfalfa meal	**	5	15	25	**	High fiber
Bakery co-product	15	30	*	*	*	Variability
Barley	*	*	*	*	*	High fiber
Corn	*	*	*	*	*	None
Corn DDGS	20	20	40	40	10	High fiber, pork fat quality
Corn gluten feed	5	5	15	40	10	Variability, high fiber
Corn hominy feed	**	20	60	60	60	Low energy
Fat / Oils	5	5	5	**	5	Handling
Milo / Sorghum	*	*	*	*	*	None
Molasses	5	5	5	5	5	Feed processing
Oats	15	30	40	*	10	High fiber
Oat groats	*	*	*	*	*	None
Rye	**	10	30	20	10	Variability, anti-nutritional factor (ergot)
Soybean hulls	5	5	10	25	5	High fiber, low bulk density
Sugar beet pulp	**	5	15	50	10	High fiber
Triticale	20	30	*	*	40	Variability, high fiber
Wheat hard	*	*	*	*	*	None
Wheat bran	5	5	20	30	10	High fiber
Wheat middlings	5	10	35	*	10	High fiber, low bulk density
Whey, dried	40	30	**	**	**	High lactose
Whey permeate	30	25	**	**	**	High lactose

Adapted from National Swine Nutrition Guide (2010).

[1]Suggested maximum inclusion percentage rates for energy sources.

*No limitation for inclusion in the diet.

**Inclusion in the diet is not practical or economical.

Energy Sources for Swine Diets

Fats and Oils

Fats and oils contain approximately 2.5 times the amount of energy as cereal grains and are considered to be highly digestible energy sources for swine. Supplemental fats and oils are commonly added to swine diets to increase energy density, but also to reduce dust, improve diet palatability, and supply essential fatty acids. The inclusion of fats and oils in swine diets is discussed in this fact sheet.

Fat composition

Fats and oils are mainly composed of fatty acids, which differ in chain length and degree of saturation. The number of carbons in the chain determines the classification of fatty acids in short-chain (C1-5), medium-chain (C6-12), or long-chain fatty acids (C13-21). The bond between carbons determines the degree of saturation of fatty acids as saturated (single bonds) or unsaturated (double bounds). Animal fats contain more saturated fatty acids and are solid at room temperature, whereas vegetable oils have more unsaturated fatty acids and are liquid at room temperature.

Animal fats, such as choice white grease, beef tallow, and poultry fat, are derived from rendering whereas vegetable oils are extracted from seeds, such as corn oil, soybean oil, and canola oil. Also, waste cooking oil or yellow grease is produced from rendering. These sources of fat and oils are available for feed-grade use in swine diets either as a single source or as a blend.

Fat quality

Fat quality greatly influences digestibility of fat and, consequently, the energy value of a fat source. Fat quality is determined by chain length, degree of saturation, free fatty acid content, and impurities. Short- and medium-chain fatty acids are more easily digested than long-chain fatty acids. Unsaturated fatty acids have higher digestibility than saturated fatty acids, and the ratio of unsaturated to saturated fatty acids improves the energy value of dietary fat as the ratio increases. Consequently, pigs make better use of vegetable oils than animal fat sources. Also, fat sources with low free fatty acid content and less impurities have higher energy value.

Fat oxidation

Fat oxidation causes degradation of fatty acids, rancidification, and consequently reduction in energy level (Kerr et al., 2015). Fat oxidation is described in three stages: initiation, propagation, and termination, with each stage producing and consuming different compounds. In the initiation stage, free radicals and hydroperoxides are produced as primary oxidation products, which affect fat quality and also have the potential to form secondary and tertiary oxidation products, such as aldehydes, ketones, alcohols, hydrocarbons, and acids, during propagation and termination that also have detrimental effects fat quality (Shurson et al., 2015).

Fat analysis

Analysis of fat sources is performed as an attempt to determine fat composition, quality, and feeding value. Common measures of fat quality include color, fatty acid profile, free fatty acid content, degree of unsaturation, saponification value, and impurities including moisture, insolubles, and unsaponifiables (MIU). These measurements are generally used to determine fat composition and to ensure the quality specifications are met (**Table 1**), but provide no information about feeding value (Shurson et al., 2015). The feeding value is assessed by measures of fat oxidation, but no single analysis adequately determines fat oxidation because of the different compounds produced during fat oxidation. Using peroxide value, thiobarbituric acid reactive substances, and anisidine value to measure compounds at different stages of oxidation is recommended to provide an accurate assessment of fat oxidation and rancidification (Kerr et al., 2015; Shurson et al., 2015).

Table 1. Common measures of fat quality and oxidation

Measures	Recommended levels
Total fatty acid content	≥ 90%
Free fatty acid content	≤ 10%
Moisture	≤ 0.5-1%
Insolubles	≤ 0.5%
Unsaponifiables	≤ 1%
Total MIU	≤ 2%
Peroxide value	≤ 5 mEq

From Azain (2001).

Measures of fat quality

- **Color**: ranging from 1 (light) to 45 (dark).
- **Fatty acid profile**: relative amount of individual fatty acids.
- **Free fatty acid content**: amount of fatty acids not bound to a carbon chain.
- **Total fatty acid content**: amount of free fatty acids and fatty acids bound to a carbon chain.
- **Iodine value**: estimate of degree of unsaturation, expressed as grams of iodine absorbed by 100 g of fat. The greater the iodine value, the greater the degree of unsaturation.
- **Saponification value**: estimate of fatty acid chain length, expressed as the amount of caustic soda needed to turn 1 g of fat into soap. The greater the saponification value, the lower the chain length.
- **Moisture:** amount of moisture.
- **Insolubles**: amount of materials that have no energy value, such as dirt, fiber, or hair.
- **Unsaponifiables**: amount of compounds that do not degrade upon mixing in alkaline solution, such as sterols, pigments, or vitamins.

Measures of fat oxidation

- **Peroxide value (PV)**: estimate of peroxides and hydroperoxides produced during the initiation of fat oxidation.
- **Thiobarbituric acid reactive substances (TBARS)**: estimate of malondialdehyde produced during propagation of fat oxidation.
- **Anisidine value (AnV)**: estimate of aldehydes produced during propagation of fat oxidation.

Antioxidants

Antioxidants can be added to fats and oils to reduce fat oxidation, control rancidity, maintain palatability, and prolong storage time, particularly in diets with high amounts of fat or manufactured in warm climates. However, antioxidants cannot reverse fat oxidation once it occurs. Commercial antioxidant products commonly include ethoxyquin, butylated hydroxytoluene (BHT), butylated hydroxyanisole (BHA), propyl gallate, citric acid, ethylenediamine-tetra-acetic acid (EDTA), or a combination of these antioxidants (Kerr et al., 2015). More information about the use of antioxidants in swine diets in Feed Additives in Swine Diets - Antioxidants.

Fat inclusion level

Fats are typically added up to 5% in swine diets. In the nursery, the addition of 3 to 4% fat is mainly used to improve the pelleting process of initial diets with high levels of lactose. In grow-finish diets, 1 to 5% fat is used to improve growth performance, with generally an improvement of feed efficiency close to 2% and average daily gain close to 1% for every 1% added fat. In lactation, 3 to 5% fat is used to increase dietary energy density. Fat is not typically added in gestation diets.

The addition of fat above 5% in meal diets normally leads to handling issues due to bridging of feeders and caking of mixers, whereas in pelleted diets leads to inferior pellet quality. Diets containing high levels of added fat are also predisposed to become rancid during prolonged storage or exposure to high temperatures.

The fat inclusion level should be based on an economic analysis to determine the most economical level considering the value of incremental changes in energy on production indicators and the market price. A production tool has been developed to aid in determining the dietary energy level in the grow-finish phase (Net Energy Model).

Fat use by the pig

The digestibility of fat is low in weanling pigs but the ability to digest fat increases with age, particularly for animal fats compared with vegetable oils. The young pig seems to require a more digestible fat sources rich in unsaturated and short-chain fatty acids for efficient energy utilization than the growing-finishing pig (Gu and Li, 2003). Vegetable oils like soybean oil and coconut oil are high quality sources of energy for weanling pigs (Weng, 2016), but are typically more expensive compared to animal sources like choice white grease.

The pig deposits fat in the same fatty acid profile as the dietary fat. This characteristic is particularly important in growing-finishing pigs because the composition of dietary fat is a determinant of carcass fat quality. Diets with vegetable oils are rich in unsaturated fatty acids and increase the iodine value and softness of carcass fat. The iodine value estimates the degree of unsaturation of carcass fat, with higher iodine value associated with softer pork fat (Benz et al., 2011). Soft pork fat is undesirable because it affects the ability to process pork bellies and to meet specifications of fresh cuts of pork. Some pork processing plants have established a maximum allowable iodine value cutoff, which may limit the amount of fat sources, especially unsaturated fats or oils, in finishing diets.

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Protein Sources for Swine Diets

The main plant protein sources for swine are soybean meal, canola meal, sunflower meal, cottonseed meal, and field peas. Animal protein sources such as spray-dried blood products, meat and bone meal, and fish meal also can be used in swine diets. The most common protein sources used in swine diets are discussed in this fact sheet.

Selection of protein sources

The decision of selecting a protein source for swine diets must consider many factors, including amino acid profile and digestibility, energy content, presence of anti-nutritional factors, variability in nutrient concentration, ability to consistently source a high-quality ingredient, cost, and production goals. Also, lysine content and digestibility often dictate the value of a protein source because it is the most limiting amino acid in most swine diets. **Table 1** presents the typical use of protein sources in swine diets considering some limiting factors.

Plant protein sources

Plant protein sources provide most of the protein in swine diets. Soybean meal is the leading protein source for swine due to its superior quality and amino acid profile. Soybean meal is generally the base to which alternative plant protein sources are compared.

Soybean products

Soybeans are the most widely used protein in the world and is the primary protein source in most swine diets. Soybean products used in swine diets include soybean meal, full-fat soybeans, fermented soybean meal, enzyme-treated soybean meal, soy protein concentrate, and soy protein isolate.

Soybeans contain anti-nutritional factors that reduce nutrient utilization, most notably trypsin inhibitors. The trypsin inhibitors have to be inactivated by heating or toasting soybeans prior to use in swine diets. Raw soybeans are not recommended for use as such in swine diets.

Pigs have a transitory hypersensitivity reaction to soybean meal induced by allergenic proteins, namely glycinin and β-conglycinin, and indigestible carbohydrates of soybeans. Pigs experience a period of poor nutrient absorption and low growth performance following the first exposure to a diet with high amounts of soybean meal (Li et al., 1990). The effects are transitory and pigs develop tolerance after 7 to 10 days (Engle, 1994). To alleviate the effects during this period, pigs are gradually acclimated to diets with increasing amounts of soybean meal after weaning. Furthermore, soybean meal can be further processed to remove the allergenic compounds and improve the utilization of soy proteins by weanling pigs (Jones et al., 2010).

♦ Soybean meal

Soybean meal is the standard protein source in swine diets and is used as the reference ingredient for protein quality. The amino acid profile, balance, and digestibility in soybean meal is better than any other plant protein source used in swine diets.

Soybean meal is produced from hulled or dehulled soybeans. Dehulled soybean meal is often referred to as high-protein soybean meal and contains approximately 48% crude protein and 3% lysine content, whereas hulled soybean meal contains approximately 44% crude protein and 2.8% lysine content and is referred to as low-protein soybean meal (NRC, 2012). Standardized ileal digestibility of lysine and most amino acids is above 85 to 90% (Cervantes-Pahm and Stein, 2010).

Processing methods to extract oil from soybeans include expelling and solvent extraction. In the expelling method, oil is mechanically extracted from soybeans after an extrusion process is used to inactive trypsin inhibitors. In the solvent extraction method, oil is extracted using a solvent and then a toasting process is used to inactive trypsin inhibitors. The expelled soybean meal contains higher oil content than solvent-extracted soybean meal because mechanical extraction is less efficient in de-oiling soybeans. The oil content in dehulled, solvent-extracted soybean meal is around 1.5% (NRC, 2012).

♦ Full-fat soybeans

Full-fat soybeans are produced by avoiding the oil extraction process after extrusion of soybeans. Properly processed full-fat soybeans are a good source of both protein and energy. The critical factor during extrusion is the prevention of over- or under-processing, since either reduce the nutritional value of full-fat soybeans.

Full-fat soybeans have an oil content of approximately 15% (NRC, 2012), which is a means of providing oil to the diet. However, full-fat soybeans contain less crude protein (35 to 40%) and lysine (2%) than soybean meal (NRC, 2012).

♦ Fermented or enzyme-treated soybean meal

Further-processed soybean meal by microbial fermentation or enzymatic treatment is done to reduce the allergenic proteins and indigestible carbohydrates of soybeans (Stein et al., 2016). Microbial fermentation is usually accomplished by the inclusion of microbes to soybean meal, such as *Aspergillus oryzae*, *Bifidobacterium lactis*, *Lactobacillus subtilis*, among others. Enzymatic treatment is commonly performed by inclusion of proprietary enzymes and yeast to soybean meal (Stein et al., 2016).

Fermented or enzyme-treated soybean meal have greater concentration of crude protein than soybean meal, approximately 50 to 55% (Cervantes-Pahm and Stein, 2010; Jones et al., 2010). However, the standardized ileal digestibility of most amino acids and particularly lysine is lower in fermented or enzyme-treated soybean meal compared to conventional soybean meal (Cervantes-Pahm and Stein, 2010). The reduction in digestibility of amino acids is due to heat during the drying process to produce fermented or enzyme-treated soybean meal.

♦ Soy protein concentrate and isolate

Soy protein concentrate and isolate are high protein products derived from soybeans.

Soy protein concentrate is produced from dehulled, de-oiled soybeans (or soy flakes). The concentration of protein is increased by removing most of the soluble non-protein constituents. Soy protein concentrate contains at least 65% crude protein (NRC, 2012).

Soy protein isolate is also produced from dehulled, de-oiled soybeans (or soy flakes). The process starts by removing most of the soluble non-protein constituents and then the isolation of protein is produced by precipitating the protein in solution. Soy protein isolate is the most concentrated soy protein source and contains at least 85% crude protein (NRC, 2012).

During processing of soy protein concentrate and isolate, the allergenic proteins and indigestible carbohydrates of soybeans are mostly removed (Stein et al., 2016). However, the antinutritional factor trypsin inhibitor might be present in greater quantities compared to soybean meal because processing does not necessarily involve heat-treatment (Cervantes-Pahm and Stein, 2010).

Canola meal

Canola meal is a by-product of oil extraction from canola seeds. Varieties were developed with reduced concentrations of the anti-nutritional factor glucosinolates and referred to as canola in Canada and United States, and double-low rapeseed or 00-rapeseed in Europe. Glucosinolates are goitrogenic compounds that affect the thyroid function and iodine metabolism, impairing feed intake and growth performance of pigs fed diets with high concentrations (Parr et al., 2015). The concentration of glucosinolates in modern varieties is generally less than 30 µmol/g and it varies in canola meal depending on the extent of degradation during toasting (Mejicanos et al., 2016).

Canola meal contains between 35 to 40% crude protein and 2% lysine content (NRC, 2012). Compared to soybean meal, canola meal contains lower crude protein and lysine content but greater concentration of methionine and cysteine. Standardized ileal digestibility of lysine and most amino acids is lower than soybean meal, approximately 70 to 75% (Cervantes-Pahm and Stein, 2010).

Recently, new varieties of high-protein canola meal were developed that contain approximately 45% crude protein (Liu et al., 2014). Although the crude protein value is closer to that of soybean meal, the amino acid digestibility in high-protein canola meal is similar to canola meal and, therefore, less than soybean meal.

The fiber content of canola meal is between 20 to 25% NDF and 3 times greater than soybean meal due to the use of hulled canola seeds (NRC, 2012). The high fiber content reduces the energy value of canola meal.

Sunflower meal

Sunflower meal is a by-product of oil extraction from sunflower seeds. Sunflower meal is free of most anti-nutritional factors.

Sunflower meal contains approximately 30% crude protein and 1% lysine content (NRC, 2012). Similar to canola meal, sunflower meal contains lower crude protein and lysine content but greater concentration of methionine and cysteine than soybean meal. Standardized ileal digestibility of lysine and most amino acids is lower than soybean meal, approximately 75 to 80% (Cervantes-Pahm and Stein, 2010).

The fiber content of sunflower meal is very high, approximately 30% NDF in dehulled sunflower meal, which is around 4 times greater than soybean meal (NRC, 2012). The inclusion of sunflower meal in swine diets is mostly limited by its high fiber content (González-Vega and Stein, 2012).

Cottonseed meal

Cottonseed meal is a by-product of oil extraction from cotton seeds. The limitation to the use of cottonseed meal in swine diets is the anti-nutritional factor gossypol found in the pigment glands of cotton seeds. The free form of gossypol is toxic and not allowed over 100 ppm in complete diets for pigs (Gadelha et al., 2014). Heat processing of cotton seeds is used to inactivate gossypol, but heating allows free gossypol to bind to lysine and reduces lysine digestibility (González-Vega and Stein, 2012). New varieties of cotton seeds commonly referred to as glandless cottonseed do not contain gossypol, but unfortunately are not common (Stein et al., 2016).

Cottonseed meal contains around 40% crude protein and 1.5% lysine content (NRC, 2012). Compared to soybean meal, cottonseed meal contains lower crude protein and lower concentration of lysine and most essential amino acids. Standardized ileal digestibility of lysine and most amino acids is lower in cottonseed meal than in any other oilseed meal, approximately 60% (Cervantes-Pahm and Stein, 2010).

The fiber content of cottonseed meal is between 20 to 25% NDF, which is 3 times greater than soybean meal (NRC, 2012).

Field peas

Field peas are predominantly produced in Canada and temperate areas where oilseeds are not grown. Field peas are pulses that can fix most of their own nitrogen and do not require substantial use of nitrogenous fertilizer for cultivation, which considerably reduce the environmental concerns (White et al., 2015). Field peas contain low concentrations of the anti-nutritional factors trypsin and chymotrypsin inhibitors, which are usually inactivated by heat processing.

Field peas contain around 22% crude protein and relatively high lysine content, around 1.5% (NRC, 2012). Compared to soybean meal, field peas have considerably lower crude protein, lysine, methionine, cysteine, and tryptophan. Standardized ileal digestibility of lysine and most amino acids is similar to that of soybean meal, around 80% (Stein et al., 2016).

Field peas have a relatively high energy value compared to other oilseed meals. This is a result of relatively low fiber (13% NDF) and high starch (43%) content in field peas (NRC, 2012), which is similar to the composition of some cereal grains.

Animal protein sources

Animal protein sources have been commonly used to minimize soybean meal inclusion in initial nursery diets and encourage feed intake in weanling pigs. Animal protein sources are typically palatable and contain highly digestible amino acids. However, animal protein sources are more expensive and variability in composition is often greater than plant protein sources.

Biosecurity concerns arise from the potential disease transmission via animal-sourced ingredients, particularly porcine-based. Animal protein sources typically undergo a thermal processing that eliminates most pathogens, but post-processing recontamination can be a concern. In addition, some pork marketing programs may limit the use of animal protein sources in swine diets.

Spray-dried blood products

Spray-dried blood products are by-products obtained from swine and bovine harvesting plants. The whole blood is collected in chilling tanks and prevented from coagulating by adding an anticoagulant. Spray-dried blood cells and spray-dried plasma are produced by separating the blood fractions, whereas spray-dried blood meal contains both blood cells and plasma (Almeida et al., 2013).

Spray-dried blood products contain high concentration of crude protein (75 to 90%) and lysine (7 to 8%) (NRC, 2012). Standardized ileal digestibility of lysine and most amino acids is high, above 95 to 95% (Almeida et al., 2013). However, lysine availability is reduced with use of excessive heating in spray-dried blood products.

The use of spray-dried blood products requires attention to an favorable balance of branched-chain amino acids due to the high concentration of leucine but low concentration of isoleucine and valine, particularly in spray-dried blood cells or blood meal (Kerr et al., 2004; Goodband et al., 2014). Also, the concentration of methionine is low in all spray-dried blood products. The inclusion of other protein sources or supplementation of diets with feed-grade amino acids is important to adjust the amino acid profile in diets with spray-dried blood products (Remus et al., 2013).

Spray-dried blood products may vary substantially in composition and quality according to source and processing methods. The application of heat is critical to eliminate pathogens (Narayanappa et al., 2015), but post-processing recontamination can be a concern. In order to minimize the risk of disease transmission via feed ingredients, it is advisable to only use non-porcine-derived blood products.

Meat and bone meal

Meat and bone meal is a by-product from various tissues obtained from harvesting plants. Meat and bone meal contains high concentrations of crude protein (50 to 55%), lysine (2.5%), and most amino acids except for tryptophan (NRC, 2012). Standardized ileal digestibility of lysine and most amino acids is low, approximately 65 to 80% (Kong et al., 2014). Moreover, lysine availability is further reduced with use of excessive heating during processing of meat and blood meal.

Meat and bone meal is an excellent source of calcium and phosphorus, providing the minerals in high concentration and with a high phosphorus bioavailability (Traylor et al., 2005).

Meat and bone meal quality and composition may vary substantially according to the raw materials characteristics. The thermal processing of meat and bone meal is critical to eliminate pathogens, but post-processing recontamination can be a concern. In order to minimize the risk of disease transmission via feed ingredients, it is advisable to only use non-porcine-derived meat and bone meal.

Poultry meal

Poultry meal is a by-product from viscera and various tissues obtained from poultry harvest. Poultry meal contains high concentration of crude protein (60 to 65%), lysine (4%), and most amino acids except for tryptophan (NRC, 2012). The digestibility of amino acids can be affected by the ash content of poultry meal. The ash content is directly related to the level of bone included in poultry meal and is a measure associated with low digestibility and inferior quality (Keegan et al., 2004). Moreover, lysine availability is further reduced with use of excessive heating during processing of poultry meal.

Poultry meal quality and composition may vary substantially according to the raw materials characteristics. The thermal processing of poultry meal is critical to eliminate pathogens, but post-processing recontamination can be a concern.

Fish meal

Fish meal is a product obtained by processing whole fish or fish waste. Fish meal typically contains high concentration of crude protein (60 to 65%) and lysine (4.5%), favorable amino acid profile, and omega-3 fatty acids (NRC, 2012). Standardized ileal digestibility of lysine and most amino acids is high, approximately 85% (Cervantes-Pahm and Stein, 2010).

The inclusion of fish meal in swine diets enhances palatability and usually increases feed intake. However, fish meal quality can vary considerably depending on the species of fish, raw fish freshness, and processing method (Kim and Easter, 2001; Jones et al., 2018). Fish solubles, also known as stickwater concentrate, is a by-product rich in B vitamins and minerals derived from fish meal processing. The amount of fish solubles is variable in fish meal, generally found at 8 to 15%, but it is not associated with fish meal quality (Jones et al., 2018).

Currently, there is no single laboratory test that provides a general estimate of fish meal quality. Analysis of mineral content and fat can be used as an indicative of fish meal feeding value. Fish meal with high mineral content (> 20%) and lower fat level (< 7.5%) is generally from fish offal and contains lower feeding value compared to fish meal from whole fish. Freshness of raw fish can be estimated by analysis of total volatile nitrogen. Values below 0.15% total volatile nitrogen generally indicate good fish meal freshness. Bacterial analysis is important to assess quality of fish meal, as *Salmonella* can be transmitted via fish meal (Morris et al., 1970).

Porcine intestinal mucosa products

Porcine intestinal mucosa products are by-products of the pharmaceutical industry obtained from processing of porcine intestinal mucosa to extract the anticoagulant heparin. The mucosa linings are enzymatically hydrolyzed after extraction of heparin and co-dried with plant proteins to produce porcine intestinal mucosa products. Commercially available products are generally referred to as enzymatically-hydrolyzed intestinal mucosa, dried porcine solubles, or peptones.

Porcine intestinal mucosa products provide small peptides that are easily digestible by pigs. The concentration of crude protein is high (50 to 60%) and amino acid profile is favorable (Myers et al., 2014). Standardized ileal digestibility of lysine and most amino acids is high, above 80 to 85% (Sulabo et al., 2013).

Variation in composition of porcine intestinal mucosa products is due to different plant proteins used as carriers during drying and processing of intestinal mucosa (Jones et al., 2010; Myers et al., 2014). The thermal processing of porcine intestinal mucosa products is critical to eliminate pathogens, but post-processing recontamination can be a concern.

Spray-dried egg

Spray-dried egg is a by-product from the egg industry produced only from eggs without shell that do not meet the quality standards for human consumption. Spray-dried egg contains high concentration of crude protein (50%), lysine (3.5%), and favorable amino acid profile (NRC, 2012). Spray-dried egg is also a good source of energy.

Spray-dried egg provides bioactive compounds, such as antimicrobial proteins (lysozyme) and immunoglobulins (IgY). The composition of spray-dried egg is thought to provide benefits to improve health (Song et al., 2012). Moreover, hens can be immunized against pathogens, such as enterotoxigenic *Escherichia coli*, and the hyperimmunized eggs serve as a pathogen-specific antibody source (Da Rosa et al., 2014).

Whey products

Whey is derived from milk curdling during production of milk products like cheese and yoghurt (Grinstead et al., 2000). The whey is separated from the curd and processed into whey products, including dried whey, whey protein concentrate, and whey permeate. Whey products are sources of both protein and lactose.

Dried whey is produced by removing most of the water from liquid whey. The drying process can be accomplished by spray drying or roller drying. Spray-drying is the preferred method to prevent over-heating of whey because of the fast evaporation at lower temperatures compared to roller-drying method (Grinstead et al., 2000). Dried whey contains 11 to 12% crude protein and high lactose concentration, approximately 72% (NRC, 2012).

Whey protein concentrate is produced by having an additional process of ultrafiltration of liquid whey before the drying process (Grinstead et al., 2000). The ultrafiltration process concentrates the whey protein and removes most of the lactose. Whey protein concentrate contains 75 to 80% crude protein and low lactose concentration, generally around 5% (NRC, 2012). Whey protein concentrate is an edible-grade product in high demand by the food industry, limiting its availability for use in swine diets.

Whey permeate is a by-product from the ultrafiltration process of liquid whey to produce whey protein concentrate. Whey permeate contains most of the lactose that is removed from the ultrafiltration process. Whey permeate contains low crude protein (3.5%) and high lactose concentration, approximately 80% (NRC, 2012).

Yeast protein source

Dried fermentation biomass

Dried fermentation biomass consists of residual material from the feed-grade amino acid production. Feed-grade amino acids are derived from amino acid-producing bacterium in a process that requires a carbon source (sugars, typically from corn) and a nitrogen source (yeast extract) for bacterial fermentation. The fermentation biomass left after extraction of crystalline amino acids is used to produce dried fermentation biomass.

Dried fermentation biomass contains high concentration of crude protein (around 80%), lysine, and essential amino acids (Sulabo et al., 2013; Almeida et al., 2014). Standardized ileal digestibility of lysine and most amino acids is high, above 90% (Sulabo et al., 2013; Almeida et al., 2014).

The amino acid-producing bacteria within the dried fermentation biomass are not harmful to pigs, but a structural component of Gram-negative bacteria (lipopolysaccharide) may have endotoxin activity (Wallace et al., 2016), which affects feed intake.

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Table 1. Inclusion rates and limitations of common protein sources in swine diets

Ingredient	Swine diet[1] Nursery < 25 lb	Nursery > 25 lb	Grow-finish	Gestation	Lactation	Limitation
Alfalfa meal	**	5	15	25	**	High fiber
Animal plasma, spray-dried	*	*	**	**	**	Amino acid balance, cost
Blood meal or cells, spray-dried	3	3	5	5	5	Amino acid balance
Canola meal	**	5	20	15	15	Anti-nutritional factor (glucosinolates)
Corn DDGS	20	20	40	40	10	Amino acid balance
Corn germ meal	10	20	20	30	15	Protein quality, high fiber
Corn gluten meal	5	10	20	30	10	Protein quality
Cottonseed meal	**	10	10	15	**	Anti-nutritional factor (gossypol), high fiber
Egg protein, spray-dried	10	*	**	**	**	Cost
Field peas	15	30	40	15	25	Anti-nutritional factor (trypsin inhibitor)
Fish meal	15	20	**	**	**	Variability
Meat and bone meal	5	10	*	*	*	Variability, high minerals
Meat meal	5	10	*	*	*	Variability, high minerals
Skim milk, dried	*	*	**	**	**	Cost
Poultry meal	5	5	*	*	*	Variability, high minerals
Soy protein concentrate	20	*	**	**	**	Palatability
Soy protein isolate	*	*	**	**	**	Cost
Soybean meal	25	*	*	*	*	None
Soybean, full-fat	25	*	*	*	*	Anti-nutritional factor (trypsin inhibitor)
Sunflower meal	**	5	*	*	*	High fiber
Wheat gluten	10	*	*	*	*	Low lysine
Whey, dried	40	30	**	**	**	High lactose
Whey permeate	30	25	**	**	**	High lactose
Whey protein concentrate	*	*	**	**	**	Availability, cost

Adapted from National Swine Nutrition Guide (2010).
[1]Suggested maximum inclusion percentage rates for protein sources.
*No limitation for inclusion in the diet.
**Inclusion in the diet is not practical or economical.

Mineral Sources for Swine Diets

The mineral content of grains and oilseeds commonly used in swine diets is often found at low concentration and availability. Consequently, it is essential to balance the diets using supplemental mineral sources to meet the requirements. The sources of macrominerals and trace minerals used in swine diets are discussed in this fact sheet.

Macrominerals

Macrominerals or major minerals need to be supplied in larger amounts in swine diets. The requirements for and dietary concentrations of macrominerals are generally expressed as a percentage (%) of the diet. Calcium, phosphorus, sodium, and chloride are the typical macrominerals added to swine diets.

Calcium and phosphorus

Calcium and phosphorus are essential in skeletal structure development and maintenance, lean tissue deposition, muscle contraction, and many other physiological functions. Calcium and phosphorus are the most abundant minerals in the pig and about 99% of the calcium and 80% of the phosphorus in the body are found in the skeleton. Consequently, deficiency of calcium and phosphorus results in impaired bone mineralization, reduced bone strength, and decreased growth. Clinical signs of deficiency include rickets in growing pigs and osteoporosis in sows, which are manifested as lameness and fractures. The deficiency is exacerbated during lactation as sows mobilize calcium from bone reserves to meet the demand for milk production, which can result in 'downer sows' in late lactation and post-weaning.

To prevent deficiency, swine diets must supply the individual requirements of calcium and phosphorus but also to provide an adequate ratio of one mineral to the other. The calcium:phosphorus ratio greatly influences the absorption and retention of both minerals. In general, wide calcium:phosphorus ratios or excessive calcium and deficient phosphorus concentrations interfere with phosphorus absorption (Reinhardt and Mahan, 1986).

Grains and oilseeds used in swine diets are typically low in calcium and have most of the phosphorus unavailable to the pig. Phytate is the storage form of phosphorus in feedstuffs of plant origin and the enzyme phytase is required to release phosphorus from phytate for absorption (Cowieson et al., 2016). As endogenous phytase activity is negligible in swine, exogenous microbial phytase is commonly used in swine diets to enhance phosphorus release from phytate. Phytase also releases calcium that can be bound to phytate. Furthermore, both calcium and phosphorus are supplemented in the diet by inorganic sources. Importantly, many inorganic sources supply both calcium and phosphorus, which require simultaneous adjustments of the amount of each source in the diet.

Sodium and chloride

Sodium and chloride are involved in nutrient absorption, electrolyte balance, and regulation of pH. Salt or sodium chloride is the most common source of sodium and chloride, composed of approximately 40% sodium and 60% chloride. The supplementation of diets with salt is essential because sodium and chloride are low in grains and oilseeds used in swine diets. However, dietary supplementation of salt is usually reduced in diets with spray-dried blood products, dried whey, or co-products from the food or pet food industry due to the high concentration of sodium and chloride in these ingredients.

The requirements for sodium and chloride are greater for nursery pigs and abruptly decrease for grow-finish pigs and sows (NRC, 2012; Shawk et al., 2018a,b). Diets deficient in salt result in decreased growth performance because of reduced feed intake and poor feed efficiency. Diets with high levels of salt are generally well tolerated if drinking water is available. However, toxicity quickly develops if drinking water is not available.

Magnesium and potassium

Grains and oilseeds used in swine diets typically provide magnesium and potassium in sufficient quantities to meet the requirements. Therefore, no other sources of magnesium and potassium are commonly used in swine diets.

Trace minerals

Microminerals or trace minerals need to be supplied in smaller amounts in swine diets, with the requirements for and dietary concentrations of trace minerals generally expressed as parts per million (ppm or mg/kg) or milligrams per pound (mg/lb) of diet. Because of the smaller amounts, trace minerals are often added in the diets in the form of a trace mineral premix. Zinc, copper, iron, manganese, iodine, and selenium are the typical trace minerals included in a trace mineral premix for swine. Iron is also provided via injectable iron in young piglets.

Zinc

Zinc is an important component of many enzymes and participates in the metabolism of carbohydrates, proteins, and lipids. Zinc is found in grains and oilseeds at low concentration and mostly associated with phytate, which makes zinc unavailable to the pig. Zinc deficiency is characterized by a skin condition called parakeratosis, low growth rate, and impaired reproductive performance. Zinc toxicity depends upon source, dietary level, and duration of feeding, but generally the maximum tolerable dietary level for swine is set at 1,000 ppm with the exception of zinc oxide, which may be included at higher levels (NRC, 2012) for short periods of time immediately after weaning.

Pharmacological levels of dietary zinc between 2,000 and 3,000 ppm is a common recommendation to nursery diets to reduce post-weaning diarrhea and improve growth performance (Hill et al., 2000; Shelton et al., 2011). These effects have been consistently demonstrated with dietary zinc provided as zinc oxide (ZnO) (Hill et al., 2001; Hollis et al., 2005; Walk et al., 2015), while zinc sulfate ($ZnSO_4$) has greater potential to induce toxicity (Hahn and Baker, 1993). Organic sources of zinc with greater bioavailability have not consistently demonstrated the same benefits as zinc oxide when organic zinc is added at lower levels (Hahn and Baker, 1993; Carlson et al., 2004; Hollis et al., 2005).

Copper

Copper is an important component of many enzymes and participates in iron absorption and synthesis of hemoglobin. Copper is found in grains and oilseeds probably at adequate quantities to meet the requirements, but determination of copper requirements of pigs is scarce. Copper deficiency signs include anemia and low growth rate. Copper toxicity occurs at levels above 250 ppm when fed for a long period of time (NRC, 2012).

Pharmacological levels of dietary copper between 125 and 250 ppm is commonly used in the diet to enhance fecal consistency in nursery pigs and improve growth performance in both nursery and grow-finish pigs (Bikker et al., 2016; Coble et al., 2017). The most commonly used source of dietary copper is copper sulfate ($CuSO_4$) (Cromwell et al., 1998), but tribasic copper chloride (TBCC) is as effective as copper sulfate in promoting growth performance (Cromwell et al., 1998; Coble et al., 2017). Organic sources of copper with greater bioavailability, such as Cu-amino acid chelate, also seem to have the potential to influence growth performance (Pérez et al., 2011; Carpenter et al., 2018).

Iron

Iron is an important component of many enzymes and is essential for synthesis of hemoglobin. Iron is low in grains and thereby commonly supplemented from inorganic sources in a trace mineral premix. Newly born piglets develop iron deficiency during lactation and have to be provided with injectable iron.

Injectable iron

Piglets develop iron deficiency in the first week of life due to limited iron storages at birth, low levels of iron in sow milk, and the rapid growth rate that occurs during this early stage of life. Iron deficiency is characterized by anemia, and anemic piglets evidence low growth rate, lethargy, pale skin, and rough hair coats. Iron in excess is also prejudicial, as iron affects gut health, stimulates proliferation of bacteria, and causes diarrhea (Li et al., 2016).

Hemoglobin and hematocrit are commonly used as reliable blood criteria to indicate iron status in pigs. Hemoglobin levels of 11 g/dL or above indicate adequate blood iron status, levels of 9 to 11 g/dL indicate borderline anemia, and levels of 9 g/dL or below indicate an anemic condition (Bhattarai and Nielsen, 2015). For hematocrit, values above 30% indicate adequate blood iron status (Perri et al., 2016).

Iron injection in piglets is a well-stablished practice to prevent iron deficiency and anemia. The injection is administered intramuscularly and preferentially in the neck area of piglets. The most commonly used sources of iron are iron dextran and gleptoferron, which have shown similar efficacy in preventing iron deficiency in piglets (Morales et al., 2018). However, absorption of iron seems to be greater with gleptoferron due to its potentially greater iron bioavailability (Morales et al., 2018).

A single dose of 200 mg of injectable iron around 4 or 6 days after birth maximizes growth performance and improves blood iron status at weaning and in the nursery (Williams et al., 2018a,b). On the other hand, providing an iron injection too soon (day 2) or too late (days 8 or 10) after birth seems to restrict pig performance (Williams et al., 2018b). The need for a second iron injection depends on the amount of iron given in the first injection. When using an injection of 200 mg of iron at 2 days of birth, an additional booster dose of 100 mg of iron midway through lactation can improve blood iron status, but it does not provide further benefits in growth performance (Williams et al., 2018a).

Manganese

Manganese is a component of many enzymes and is involved in bone development. Manganese is found in grains and oilseeds at low concentration. Manganese deficiency signs include impaired skeleton development, lameness, and low growth rate.

Iodine

Iodine is an important component of thyroid hormones and thereby is involved in regulation of metabolic rate. Feedstuffs grown in low-iodine soil, as in the case of sandy areas, are deficient in iodine. Also, canola or rapeseed may contain increased levels of goitrogenic compounds called glucosinolates that interfere with iodine metabolism. Iodine deficiency is characterized by goiter (thyroid enlargement), lethargy, and low growth rate.

Selenium

Selenium is an important component of enzymes involved in antioxidant defense. Selenium and vitamin E have closely related functions, but requirements are independent of one another. Feedstuffs grown in low-selenium soil, as is the case of many areas in the United States, are deficient in selenium. Selenium deficiency signs are similar to signs of vitamin E deficiency, which includes white muscle disease, mulberry heart disease, sudden death, and impaired reproduction. Selenium toxicity at levels of 5 to 10 ppm selenium is characterized as chronic selenosis, with signs of low growth rate and separation of the hoof at the coronary band (NRC, 2012; Gomes et al., 2014). Selenium toxicity at levels above of 10 to 20 ppm selenium is characterized as acute selenosis, with signs of posterior paralysis and lesions in the central nervous system (NRC, 2012; Gomes et al., 2014). The amount of selenium inclusion is regulated in the United States and restricted to a maximum of 0.3 ppm added selenium in any swine diet.

KSU Trace mineral premix

A suggested trace mineral premix is available at KSU Premix & Diet Recommendations. This single premix can be used in diets for all stages of production by adjusting the inclusion rate for sow, nursery, grower, and finisher diets. A sow add pack is also available for sow diets to supply the specific vitamins to enhance reproduction.

Trace minerals can be combined with vitamins in a VTM premix, but it is recommended to have separate premixes because trace minerals can affect the vitamin stability. Otherwise, VTM premix age must be monitored to ensure it is used before excess vitamin loss.

Dietary electrolyte balance

Dietary electrolyte balance represents the ratio of cations and anions in a diet and is important for acid-base status of pigs. The dietary ions that mostly influence electrolyte balance are sodium, chloride, and potassium. Dietary electrolyte balance is determined by the difference between cations and anions in the diet: Na + K - Cl. However, more comprehensive estimation of dietary electrolyte balance also takes into account the contribution of divalent ions, such as calcium, magnesium, sulfur, and potassium.

Traditionally, the optimal dietary electrolyte balance for swine is reported to be approximately 250 mEq/kg (NRC, 2012).

Mineral sources

Minerals are available in inorganic or organic forms to add in swine diets. Inorganic minerals are provided as inorganic salts like sulfates, carbonates, chlorides, and oxides. Organic minerals are provided as a complex with an organic agent like amino acids, proteins, and carbohydrates, and are therefore also called complexed or chelated minerals.

Inorganic minerals release free ions that are reactive and likely to bind to other dietary components. This characteristic can affect the stability of vitamins and minerals in the premix, as well as interfere in the absorption of minerals by the pig during digestion. Organic minerals are less likely to bind to other dietary components because the minerals are already in a complex with organic agents. The organic forms are supposed to minimize the interactions and enhance the absorption and bioavailability of minerals (Liu et al., 2014). However, greater bioavailability of organic minerals does not always result in improvements in growth (Creech et al., 2004; Ma et al., 2012) or reproductive performance (Peters and Mahan, 2008; Peters et al., 2010; Ma et al., 2014). Typically, the use of organic mineral sources is more prevalent in diets for sows and nursery pigs (Flohr et al., 2016).

Decisions on which source of mineral to use should be based primarily on price per unit of bioavailable element, with organic minerals usually being more bioavailable but inorganic minerals are typically more economical. A list of the chemical forms in which inorganic macrominerals and trace minerals are available is shown in **Table 1 and 2** (NRC, 2012).

Table 1. Inorganic sources of trace minerals and respective mineral content

Inorganic mineral	Source	Mineral content, %	Relative bioavailability, %
Zinc	Zinc sulfate (monohydrate)	35.5	100*
	Zinc oxide	72.0	50-80
	Zinc sulfate (heptahydrate)	22.3	100
	Zinc carbonate	56.0	100
	Zinc chloride	48.0	100
Copper	Cupric sulfate (pentahydrate)	25.2	100*
	Cupric chloride, tribasic	58.0	100
	Cupric oxide	75.0	0-10
	Cupric carbonate (monohydrate)	50-55	60-100
	Cupric sulfate (anhydrous)	39.9	100
Iron	Ferrous sulfate (monohydrate)	30.0	100*
	Ferrous sulfate (heptahydrate)	20.0	100
	Ferrous carbonate	38.0	15-80
	Ferric oxide	69.9	0
	Ferric chloride (hexahydrate)	20.7	40-100
	Ferrous oxide	77.8	---
Manganese	Manganous sulfate (monohydrate)	29.5	100*
	Manganous oxide	60.0	70
	Manganous dioxide	63.1	35-95
	Manganous carbonate	46.4	30-100
	Manganous chloride (tetrahydrate)	27.5	100
Iodine	Ethylenediamine dihydroiodide (EDDI)	79.5	100*
	Calcium iodate	63.5	100
	Potassium iodide	68.8	100
	Potassium iodate	59.3	---
	Cupric iodide	66.6	100
Selenium	Sodium selenite	45.0	100*
	Sodium selenate (decahydrate)	21.4	100

Adapted from NRC (2012). The inorganic mineral sources listed in italic are less commonly used sources.
*Mineral source used as standard to which other sources were compared to determine relative bioavailability.
--- No data available.

Table 2. Inorganic sources of macrominerals and respective mineral content					
Source	Calcium, %	Phosphorus, %[1]	Sodium, %	Chloride, %	Potassium, %
Bone meal, steamed	29.8	12.5	0.04	---	0.2
Calcium carbonate	38.5	0.02	0.08	0.02	0.08
Limestone	35.8	0.01	0.06	0.02	0.11
Calcium phosphate (dicalcium)	24.8	18.8	0.20	0.47	0.15
Calcium phosphate (monocalcium)	16.9	21.5	0.20	---	0.16
Calcium phosphate (tricalcium)	34.2	17.7	6.0	---	---
Phosphate, defluorinated	32.0	18.0	3.27	---	0.10
Phosphate, rock curacao, ground	35.1	14.2	0.20	---	---
Phosphate, rock, soft	16.1	9.05	0.10	---	---
Sodium chloride	0.30	---	39.5	59.0	0
Sodium carbonate	---	---	43.3	---	---
Sodium bicarbonate	0.01	---	27.0	---	0.01
Potassium chloride	0.05	---	1.0	46.9	51.4

Adapted from NRC (2012). The inorganic mineral sources listed are more commonly used sources.
[1]Values for total phosphorus. Standardized total tract digestibility (STTD) is 88.3, 81.4, and 53.4% for monocalcium, dicalcium, and tricalcium phosphate, respectively.
--- No data available.

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Vitamin Sources for Swine Diets

Vitamins are required for normal metabolism in physiological functions such as growth, development, maintenance, and reproduction. Some vitamins are produced by the pig in sufficient quantities to meet its needs while others are present in adequate amounts in feed ingredients commonly used in swine diets. However, several vitamins need to be added to swine diets in the form of a vitamin premix to avoid deficiency and obtain optimal performance. The sources of vitamins used in swine diets are discussed in this fact sheet.

Fat-soluble vitamins

Vitamins A, D, E, and K are fat-soluble vitamins and are mainly involved in tissue development, calcium and phosphorus metabolism, antioxidant defense, and blood clotting, respectively.

Vitamin A

Vitamin A is essential for vision, reproduction, and tissue development. Grains and oilseeds commonly used in swine diets have a precursor of vitamin A, β-carotene, which is converted in vitamin A in the intestine of the pig. However, β-carotene is found in low concentration and is easily degraded. Vitamin A deficiency is characterized by blindness, incoordination, reproductive failures, and low growth rate. Vitamin A toxicity develops above 20,000 IU/kg for growing pigs and 40,000 IU/kg for sows, and signs include scaly skin, rough hair coat, and incoordination (NRC, 2012).

Vitamin D

Vitamin D is essential for calcium and phosphorus absorption and thus, is important for bone mineralization. Grains and oilseeds commonly used in swine diets have a form of vitamin D which requires exposure of pigs to sunlight to become active. In enclosed swine facilities, the active form of vitamin D, vitamin D_3, needs to be supplemented in the diet. Vitamin D deficiency is characterized by rickets in growing pigs and osteoporosis in sows, which are manifested as lameness and fractures. Vitamin D toxicity develops above 2,200 IU D_3/kg for long-term feeding or 33,000 IU D_3/kg for short-term feeding, and causes mineralization of soft tissues (NRC, 2012).

Vitamin E

Vitamin E is important for antioxidant defense. Vitamin E and selenium have closely related functions, but requirements are independent of one another. Vitamin E content in grains and oilseeds commonly used in swine diets is mostly lost during storage and processing. Vitamin E deficiency signs are similar to signs of selenium deficiency, which includes white muscle disease, mulberry heart disease, sudden death, and impaired reproduction.

Vitamin K

Vitamin K is essential for blood clotting. Vitamin K is available in feedstuffs of plant origin (K_1), produced by the intestinal microbiota of pigs (K_2), and added to the diet in synthetic form (K_3). Vitamin K deficiency is characterized by prolonged blood clotting time and hemorrhages.

Water-soluble vitamins

The B-complex vitamins are water-soluble vitamins and are required as co-enzymes in several metabolic processes. The B vitamins added in swine diets are riboflavin, niacin, pantothenic acid, and vitamin B_{12}. In addition, folic acid, pyridoxine, choline, and biotin are included in sow diets due to the influence of these vitamins on reproductive performance.

Pantothenic acid

Pantothenic acid is an important component of enzymes involved in the metabolism of protein, carbohydrate, and fat. Pantothenic acid content is variable in grains and oilseeds commonly used in swine diets. Pantothenic acid deficiency causes non-specific signs, such as low growth rate, low intake, rough hair coat, diarrhea, and reproductive failure. A characteristic sign of pantothenic acid deficiency is a gait disorder in the rear legs, which includes tremor, stiffness, and a high-stepping gait called ‘goose stepping’.

Riboflavin

Riboflavin is an essential component of enzymes involved in the metabolism of protein, carbohydrate, and fat. Riboflavin content is typically low in grains and oilseeds commonly used in swine diets. Riboflavin deficiency causes non-specific signs, such as low growth rate, low intake, skin lesions, rough hair coat, diarrhea, and reproductive failure.

Niacin

Niacin is an important component of enzymes involved in many metabolic reactions. Grains commonly used in swine diets contain adequate amounts of niacin, but in a bound form unavailable to pigs. Niacin deficiency is characterized by skin lesions, rough hair coat, hair loss, diarrhea, vomiting, and lesions in the digestive tract.

Vitamin B_{12}

Vitamin B_{12} is an essential component of enzymes involved in several metabolic functions. Feedstuffs of plant origin do not contain vitamin B_{12}, whereas proteins of animal origin are good sources of vitamin B_{12}. Vitamin B_{12} deficiency causes non-specific signs, such as low growth rate, low intake, rough hair coat, incoordination, and reproductive failure. A typical sign of vitamin B_{12} deficiency is anemia.

Folic acid

Folic acid is mainly added to sow diets. Folic acid is involved in the synthesis of essential components for cell development and function. Grains and oilseeds commonly used in swine diets have adequate concentration of folic acid to meet the requirement of growing pigs. Folic acid supplementation in sows is particularly important for adequate development of conceptus and to improve litter size and live born piglets.

Pyridoxine

Pyridoxin is mainly added to sow diets. Pyridoxine is an essential component of enzymes involved in amino acid metabolism. Grains and oilseeds commonly used in swine diets have adequate concentration of pyridoxine to meet the requirement of growing pigs. Pyridoxine supplementation in sows is found to improve litter size and wean-to-estrus interval.

Choline

Choline is mainly added to sow diets. Choline is involved in many essential metabolic functions for cell structure, nervous function, and amino acid metabolism. Choline is present in adequate amounts in grains and oilseeds commonly used in swine diets and pigs are also able to produce choline to meet the requirements. Choline supplementation in sows is found to improve conception rate, farrowing rate, litter size, live born piglets, and weaned piglets.

Biotin

Biotin is mainly added to sow diets. Biotin is an essential component of enzymes involved in the metabolism of protein, carbohydrate, and fat. Grains and oilseeds commonly used in swine diets have adequate concentration of biotin to meet the requirement of growing pigs. Biotin supplementation in sows is found to improve litter size, live born piglets, and weaned piglets, and to enhance hoof soundness.

KSU Vitamin premix

A suggested vitamin premix is available at KSU Premix & Diet Recommendations. This single premix can be used in diets for all stages of production by adjusting the inclusion rate for sow, nursery, grower, and finisher diets. A sow add pack is also available for sow diets to supply the specific vitamins to enhance reproduction.

Vitamins can be combined with trace minerals in a VTM premix, but it is recommended to have separate premixes because trace minerals can affect the vitamin stability. Otherwise, VTM premix age must be monitored to ensure it is used before excess vitamin loss.

Vitamin sources

Synthetic vitamins are widely used in premixes for swine diets. The commercially synthesized vitamins are modified from natural vitamin forms to improve their stability, compatibility, mixability, and handling characteristics for feed supplementation. The natural source of vitamin E, d-α-tocopheryl acetate or natural vitamin E, is the only non-synthetic vitamin often used in swine diets. A list of sources of vitamins and respective units of activity is presented in **Table 1**.

The form of vitamin products determines important characteristics of vitamin quality. Vitamin forms with good stability are usually able to maintain good vitamin bioavailability. Vitamin forms with high flowability, high uniformity in mix, low dusting, and low caking provide optimal handling and mixing characteristics. Altogether, these characteristics are important because vitamins are added in such small amounts to swine diets that the presence or absence of vitamins in individual rations markedly affect performance and health.

Vitamin levels

The vitamin content of feed ingredients is usually disregarded in diet formulation because of imprecision and variation on methods of analysis, characteristics of ingredients, and degradation of vitamins in storage and processing (Gaudré and Quiniou, 2009). Thus, vitamin levels in the vitamin premix are calculated to fully supply the vitamin requirements of swine. Also, it appears to be standard practice to add a margin of safety for vitamin levels beyond the NRC (2012) requirement estimates (Flohr et al., 2016). The margin of safety intends to account for fluctuations in daily feed consumption and degradation of vitamins in storage and processing.

Vitamin stability

The stability of vitamins in a premix is critical in maintaining vitamin potency. Susceptibility to degradation varies depending on individual vitamins and on a number of factors that affect vitamin stability. Safety margins for vitamin premix formulation are usually based upon vitamin cost, presence or absence of trace minerals and choline in the premix, feed processing characteristics, environmental conditions, anticipated storage time, and expected rates of vitamin potency losses (Shurson et al., 2011).

Factors affecting vitamin stability

Vitamin stability in premixes is affected by exposure to light, heat, moisture, oxygen, and pH, and contact with other compounds. These factors subject vitamins to degradation primarily through oxidation. The long-term or multiple exposure to these factors generally magnifies the negative impact on vitamin stability. The individual vitamins vary in their susceptibility to degradation (**Table 2**). In general, the most sensitive or labile vitamins are vitamin K_3, vitamin A, pyridoxine, vitamin B_{12}, and folic acid (Shurson et al., 2011).

Vitamin stability in premixes

Premix composition affects vitamin stability, especially with regard to the presence or absence of choline and inorganic trace minerals. To maintain vitamin potency it is recommended to have vitamin premixes separated from choline and trace mineral premixes.

Choline is very hygroscopic and absorbs significant amounts of moisture from the environment, which affects the stability of other vitamins when added in the premix. Inorganic trace minerals also affect the stability of vitamins when added in the premix, as trace minerals often produce reduction and oxidation reactions in the premix. Among the inorganic trace mineral sources, the sulfates have greater effect on vitamin stability than carbonates and oxides. Use of organic trace mineral sources reduces vitamin activity losses by 40 to 50% during storage compared to adding inorganic trace minerals in a vitamin-trace mineral premix (Shurson et al., 2011).

Vitamin stability during feed processing

Some processes used in feed manufacturing affect vitamin stability (Reddy and Love, 1999). In swine diets, pelleting is typically the most aggressive process against vitamins due to exposure to heat, moisture, pressure, and abrasion. Mixing also affects vitamin stability due to abrasion and contact with other compounds in the diet.

Vitamin stability during storage

Vitamins are rather stable prior to preparation of a premix and remain reasonably stable in complete feeds. Consequently, most vitamin losses occur while the vitamin premix is under storage. Both storage time and storage conditions should be controlled for vitamin premixes. Vitamin premixes should be stored in a dry, cool, and dark place to maintain stability during storage. Also, the use of barriers such as plastic-lined bags aid in reducing the absorption of moisture.

Premixes containing vitamins exclusively can be stored for about 3 to 4 months. However, storage time should not exceed 60 days if choline and trace minerals are present in combination with vitamins in the premix.

During storage, vitamin potency can be monitored in premixes through a vitamin activity assay. Vitamin assay costs are generally expensive, which prompts the selection of one indicator vitamin to estimate the vitamin potency losses in the premix. According to Shurson et al. (2011), retinol appears to be the best indicator in the vitamin premix because of the low cost of assay, relatively high sensitivity of vitamin A to multiple factors, and high expected loss of activity per month of storage.

Technologies to improve vitamin stability

Advances in research and technology have led to the development of specialized vitamin forms to provide superior vitamin stability. Many commercial vitamin manufacturers have succeeded in enhancing stability of vitamins with spray-drying and beadlet technologies (DSM Vitamin Nutrition Compendium).

Spray-dried vitamin products are manufactured as a fine powder with high stability and good uniformity of mix, but only fair quality in terms of flowability, dustiness, and caking. Beadlets are produced by coating vitamins in gelatin or starch to prevent contact with factors affecting vitamin stability until it is digested by the pig. Beadlets are manufactured as a fine granular product with high stability and also high flowability, low dustiness, and low caking characteristics. Cross-linked beadlets are produced by coating vitamins with cross-linked gelatin proteins, which makes harder beadlets that are more resistant to the pressure and abrasion of pelleting. The inclusion of antioxidants in the beadlets provide additional protection against oxidative factors.

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Table 1. Sources of vitamins and respective units of activity				
Vitamin	Abbreviation	Principal compound	Source	Units of activity
Vitamin A	A	Retinol	Retinyl acetate	1 IU = 0.34 µg retinyl acetate
			Retinyl A palmitate	1 IU = 0.55 µg retinyl palmitate
			Retinyl A propionate	1 IU = 0.36 µg retinyl propionate
Vitamin D	D	Cholecalciferol (D_3)	Cholecalciferol (vitamin D_3)	1 IU = 0.025 µg cholecalciferol
Vitamin E	E	α-tocopherol	dl-α-tocopheryl acetate	1 mg = 1.0 IU dl-α-tocopheryl acetate
			d-α-tocopheryl acetate (natural vitamin E)	1 mg = 2.1 IU d-α-tocopheryl acetate[1]
			dl-α-tocopherol	1 mg = 1.11 IU dl-α-tocopherol
			d-α-tocopherol	1 mg = 1.49 IU d-α-tocopherol
Vitamin K	K	Menadione (K_3)	Menadione nicotinamide bisulfite (MNB)	1 Ansbacher unit = 20 Dam units = 0.0008 mg menadione
			Menadione dimethylpyrimidinol bisulfite (MPB)	
			Menadione sodium bisulfite complex (MSBC)	
Riboflavin	B_2	Riboflavin	Crystalline riboflavin	Commonly expressed as mg
Niacin	B_3	Niacinamide and nicotinic acid	Niacinamide	Commonly expressed as mg
			Nicotinic acid	Commonly expressed as mg
Pantothenic acid	B_5	Pantothenic acid	d-calcium pantothenate	1 mg = 0.92 mg d-pantothenic acid
			dl-calcium pantothenate	1 mg = 0.45 mg d-pantothenic acid
Vitamin B_{12}	B_{12}	Cobalamin	Cyanocobalamin	1 µg = 1 USP unit = 11,000 LLD units
Pyridoxine	B_6	Pyridoxine	Pyridoxine hydrochloride	1 mg = 0.823 mg pyridoxine
Choline	B_4	Choline	Choline chloride	1 mg = 0.868 mg choline
Biotin	H	Biotin	d-biotin	1 mg = 1 mg of activity
Folic acid	B_c	Pteroyglutamic acid and polyglutamate derivatives	Folic acid	1 mg = 1 mg of activity

Adapted from Reese and Hill (2010) and [1]Shelton et al. (2014). The vitamin sources listed in italic are less commonly used sources.

Table 2. Susceptibility of vitamins to factors affecting stability							
Vitamin	Abbreviation	Temperature	Humidity	Light	Oxygen	Acid pH	Alkaline pH
Vitamin A	A	Very sensitive	Sensitive	Very sensitive	Very sensitive	Sensitive	Stable
Vitamin D	D	Sensitive	Sensitive	Sensitive	Very sensitive	Sensitive	Stable
Vitamin E	E	Stable	Stable	Sensitive	Sensitive	Sensitive	Sensitive
Vitamin K	K	Sensitive	Very sensitive	Stable	Sensitive	Very sensitive	Stable
Riboflavin	B_2	Stable	Sensitive	Sensitive	Stable	Stable	Stable
Niacin	B_3	Stable	Stable	Stable	Stable	Stable	Stable
Pantothenic acid	B_5	Sensitive	Sensitive	Stable	Stable	Stable	Stable
Vitamin B_{12}	B_{12}	Very sensitive	Sensitive	Sensitive	Sensitive	Stable	Stable
Pyridoxine	B_6	Very sensitive	Sensitive	Sensitive	Stable	Sensitive	Stable
Biotin	H	Sensitive	Stable	Stable	Stable	Stable	Stable
Folic acid	B_c	Very sensitive	Sensitive	Very sensitive	Stable	Very sensitive	Stable

Adapted from DSM Vitamin Nutrition Compendium and Shurson et al. (2011).

Water in Swine Nutrition

Water is the most essential of all nutrients and is the most consumed nutrient in terms of amounts throughout its lifetime. Consequently, it seems to be of utmost importance to provide water in enough quantity and adequate quality to swine in all stages of production. The most relevant topics regarding water in swine production are discussed in this fact sheet.

Water requirements

Water accounts for as much as 80% of body weight at birth and declines to approximately 50% in a finished market pig. Water requirements are primarily associated with body weight and feed intake. Suckling piglets drink around 1.5 oz of water per day on the first days after birth and gradually increase consumption to around 1.5 cups daily by weaning at 28 days (Fraser et al., 1988; Nagai et al., 1994). Water intake during the nursing period may prevent dehydration and promote survival of piglets with low milk intake (Fraser et al., 1988). After weaning, water requirements are highly variable. In general, water requirements are commonly based on water to feed ratios, with normal ratios of 2:1 to 3:1 for nursery and grow-finish pigs, declining as pigs grow (Shaw et al., 2006).

In gestation, restricted-fed sows consume most of the water between meals and there is no relation between water and feed intake. Water requirements for gestating sows range from 3 to 6 gallons of water per day (Brumm, 2010). In lactation, sows have the greatest water requirement attributed to meeting the demands of milk production. Also, water consumption is important to encourage feed consumption in lactation. Water requirements for lactating sows range from 5 to 10 gallons per day (Kruse et al., 2011).

Factors affecting water usage

Water usage by the pigs is influenced by different factors, including environment, management, facilities, and diet. Understanding the factors affecting water usage is important to provide water to meet the requirements while controlling water wastage.

Water flow rate

Low water flow rate increases the time spent at the drinker and discourages optimal water consumption by the pigs. In contrast, high water flow rate increases water wastage. The recommended water flow rates are presented in **Table 1**.

Water pressure also influences the activation of water delivery devices by the pigs and the amount of water wastage. The recommended water pressure to facilitate activation while controlling water spilling is 20 psi.

Table 1. Recommendations for water flow rate

	Nursery	Grow-finish	Sows
Flow rate, cups/min	1-2	2-4	4
Time to fill a 16 oz bottle, sec	60-120	30-60	30

Adapted from Brumm (2006; 2010).

Waterer to pig ratio

Waterer to pig ratio of 1:25 is typical for nursery and grow-finishers in the industry. The general recommendation is to have a single waterer for every 10 to 15 pigs, typically in a 1:12 waterer to pig ratio. Providing access to water at the recommendation may improve growth performance of nursery (Sadler et al., 2008) and grow-finish pigs (Vier et al., 2018).

Waterer type and adjustment

Waterer types for pigs are generally categorized as nipples or cups. Both are designed to provide *ad libitum* water to pigs and there is no evidence that growth or reproductive performance is influenced by waterer type. Yet, waterer adjustments to the proper height for consumption is important to encourage water consumption as pigs grow. Cups and nipples mounted at a 90° angle should be adjusted at shoulder height, whereas nipples mounted at a 45° degree angle should be set at 2 to 3 inches over shoulder height.

There is a wide variation in the amount of water wastage due to waterer type and management. Nipple drinkers are more prone to water wastage than cup drinkers. With nipple drinkers, water spilling goes directly into the manure pit and pigs easily activate the nipple for recreation or by unintentionally leaning on the nipple. Nipple drinkers may require more management of waterer height and water flow to minimize water wastage. With cup drinkers, water spilling flows into a bowl placed beneath the water delivery devices and is available for pigs to drink. However, cup drinkers may also accumulate feed, urine, and feces in the bowl, whereas nipples provide a continuous supply of fresh water for pigs.

Feed form and feeder type

Water consumption is greater for pigs fed meal diets compared to pellet diets, resulting in a similar water to feed ratio when accounting for differences in feed efficiency between the feed forms (Laitat et al., 1999). The use of wet-dry feeders reduces water wastage compared to the use dry feeders and waterers (Brumm et al., 2000).

Diet composition

Water consumption is greater when dietary composition increases the need to eliminate metabolites or surplus nutrients. The increase in water consumption is noticeable when pigs are fed diets with excess salt, proteins, or minerals (Shaw et al., 2006).

Environmental conditions

The amount of water consumption by pigs varies greatly with temperature, humidity, ventilation, stocking density, flow rate, health status, and stress level. Knowledge of the daily patterns of water consumption by the pigs can serve as an indicator of unfavorable environmental conditions and a predictor of the onset of health challenges (Brumm, 2006).

Water quality

Water quality generally refers to the mineral composition, pH, and bacterial contamination of drinking water. Minerals most commonly found in ground and surface waters are sulfates, chlorides, bicarbonates, and nitrates, which form salts with calcium, magnesium, or sodium. The combined concentrations of these minerals are called total dissolved solids (Patience, 2012). The potential for water quality issues increases with heavy applications of fertilizers to fields, contamination of run-off water by animal wastes, and severe drought. Pigs are typically adaptive to a wide range of water quality, but concerns arise with elevated levels of sulfate, nitrate and nitrite in the water source.

Sulfates

Sulfates are a common cause of water quality problems. Sulfates are of special concern because of laxative effects. As a result, pigs consuming water with high levels of sulfates typically have diarrhea. Growth and reproductive performance do not seem to be adversely affected unless extreme levels of sulfates are present in drinking water. Recommended maximum sulfate level in water is 1,000 ppm (NRC, 2012).

Nitrates and Nitrites

In water, nitrates are converted to the toxic compound, nitrites. Nitrites impair the oxygen-carrying capacity of the blood by reducing hemoglobin to methemoglobin. As a result, nitrites toxicity causes low oxygenation of tissues and results in signs of cyanosis and difficulty breathing. Recommended maximum level in water is 100 ppm of nitrates plus nitrites nitrogen (NRC, 2012).

Total Dissolved Solids

Total dissolved solids (TDS) is a measure of the total minerals dissolved in a water, which is also referred to as water salinity. As many elements contribute to TDS, further analyses need to be conducted to determine specific mineral contaminants in the water. Pigs consuming water with high levels of TDS have transitory diarrhea, but health, growth and reproductive performances are not usually affected. Recommended maximum TDS level in water is 3,000 ppm (NRC, 2012).

Hardness

Hardness is the level of calcium and magnesium in the water. Water hardness contributes to the formation of scale deposits that can lead to accumulation of scale in the water system, causing nipple drinkers to become blocked. Water is considered soft if the concentration of calcium and magnesium is below 60 ppm and hard if above 120 ppm (NRC, 2012).

pH

pH is the measure of water acidity or alkalinity. Most water sources are within the acceptable pH range of 6.5 to 8.5 (NRC, 2012). Acidic water (pH lower than 5) can create corrosion and cause damage to water lines. Basic water (pH above 9) can form scale deposits and block the nipple drinkers. Moreover, water pH influences the dispersion of medications used via water application and influences proliferation and survivability of pathogens. Basic water (pH above 7) is considered a risk factor for *E. coli* diarrhea and water pH should be controlled if diarrhea is a problem.

Coliforms

Water contamination by bacteria is estimated by measuring the level of coliforms per milliliter of water. Recommended maximum level of coliforms in the water is 50 CFU/ml (NRC, 2012).

Water test and treatment

It is recommended to test water quality annually. A regular water test allows for detection of changes in water suitability for pigs. Water tests typically assess TDS, hardness, pH, and coliform count. Water samples should be collected at the beginning and at the end of water lines for analysis.

It is important to clean water lines regularly. Water lines form a biofilm and a buildup with solids over time, which increases the pathogen load, reduces the volume of water, and decreases the efficiency of chemicals and medications used via water. Water lines should undergo a treatment with hydrogen peroxide and organic acids to flush out the buildup and then a chlorine-based disinfectant should be used to reduce the pathogen load. It is worth noting that disinfectants have little to no effect on microorganisms contained in biofilms or in the presence of organic matter. After cleaning, all nipples should be checked for flow rate as biofilm and solids can reduce or plug water flow through nipples.

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Nutritional Value of Ingredients

There are different methodologies for assigning nutritional values to feed ingredients. However, consistently using the same methodology across the feed ingredients used in diet formulation is key. A common approach is to use nutritional composition databases from the National Research Council (NRC), the French National Institute for Agricultural Research (INRA), or the Brazilian Tables for Poultry and Swine. Additionally, nutritional values may be provided by the ingredient supplier. However, there are practical approaches that can be used to assign nutritional values to feed ingredients when values are not available or not similar to the reference ingredient in the databases. The approaches to practically assign values of energy, amino acids, and phosphorus to feed ingredients are discussed in this fact sheet.

Assigning energy values

Dietary energy is the most expensive component of swine diets. Precision in assigning the energy value of a feed ingredient is crucial to achieve the predicted performance and optimal feed cost.

Energy can be expressed as digestible (DE), metabolizable (ME), or net energy (NE). The DE and ME energy systems are the most widely used for evaluating ingredients because energy values are relatively easy to measure. However, the NE system is recognized as the closest ingredient energy value estimate because it takes the heat increment from digestive process and metabolism of feeds into account. Importantly, the same energy system must be consistently used across the feed ingredients used in diet formulation.

Practical approaches can be used to assign energy values to feed ingredients (Gonçalves et al., 2016).

Prediction equations

Prediction equations generally require chemical analysis input for dry matter (DM), crude protein (CP), ether extract (EE), neutral detergent fiber (NDF) or acid detergent fiber (ADF), ash, and starch to yield a predicted energy value. For an accurate ingredient analysis, following a standardized sampling procedure is key.

The NRC and the Brazilian Tables present equations for predicting NE developed by Noblet (Noblet et al., 1994). EvaPig® is a software developed by INRA in partnership with the French Association for Animal Production (AFZ) and Ajinomoto Eurolysine S.A.S. that presents equations for predicting NE based on databases from these organizations. The prediction equations for NE from INRA and the Brazilian Tables account for difference in energy digestibility between growing pigs and sows, while the NRC equations do not.

Validation experiments

Validation experiments are conducted to confirm energy values for feed ingredients (Li et al., 2017). In these experiments, the ingredient is included in increasing amounts in the diet while other nutrients are maintained at a constant level among dietary treatments. This is based on the fact that pigs tend to consume feed to meet the energy requirements, thus if the other nutrients such as lysine are maintained constant, similar growth performance is expected (Li et al., 2018).

Initially, an estimated energy value is assigned to the ingredient to formulate experimental diets, which is most often derived from nutritional tables. Then, feed efficiency or caloric efficiency are used to determine whether the energy value of the ingredient was accurately estimated. Caloric efficiency is the most commonly used criteria and is determined by estimating the amount of daily energy intake per pound of gain (kcal of NE per lb of gain).

> **Caloric efficiency**
>
> Caloric efficiency, kcal NE per lb gain =
>
> (ADFI, lb × Dietary energy, kcal NE per lb) ÷ ADG, lb

If the energy value of the ingredient was accurately estimated, a similar caloric efficiency is observed among the dietary treatments with increasing amounts of the ingredient. If the caloric efficiency is not similar, the energy level for the ingredient is likely underestimated if caloric efficiency improves with increasing amounts of the ingredient, or overestimated if caloric efficiency worsens (Li et al., 2017). The NE values of corn, distillers dried grains with solubles, canola meal, wheat middlings, soybean oil, tallow, among other ingredients have been validated through this method (Hastad et al., 2005; Wu et al., 2007; Adeola et al., 2013; De Jong et al., 2014; Graham et al., 2014; Nitikanchana et al., 2015; Li et al., 2017).

Relative values

The use of relative values can be used if 1) the feed ingredient contains a similar composition (CP, NDF, EE, ash, starch) to the reference ingredient and 2) the reference ingredient energy value is reliable (Gonçalves et al., 2016). In this method, both the new ingredient and the reference ingredient are submitted to the same approach to be assigned an energy value, which can be any of the approaches described above. The estimated energy value for the reference ingredient is then compared to its original reliable energy value. If there is a difference between estimated and original energy values, an adjustment is applied to the estimated energy value of the ingredient of interest.

For example, the estimated energy value of the ingredient of interest is 910 kcal NE/lb and the estimated energy value of corn is 1,210 kcal NE/lb, therefore the ratio is 910 ÷ 1,210 = 0.75. The adjustment is then applied on the original energy value of the reference ingredient to generate a relative energy value for the ingredient of interest. For example, if the original reliable energy value of corn is 1190 kcal NE/lb, the relative value of the ingredient of interest is 1,190 × 0.75 = 892 kcal NE/lb.

Relative value

Adjustment = Estimated energy of ingredient, kcal/lb ÷ Estimated energy of reference ingredient, kcal/lb

Relative value, kcal/lb = Adjustment × Original energy value of reference ingredient, kcal/lb

Assigning amino acid values

Protein is essential for growth and development of swine. Accurate determination of digestible amino acids in a feed ingredient is important to achieve optimum performance and because protein sources are expensive components of the diet.

Amino acid digestibility is expressed as total tract digestibility or ileal digestibility. The ileal digestibility is more accurate than total tract digestibility because amino acids are exclusively absorbed in the small intestine and microbial fermentation in the large intestine affects the recovery of amino acids. The ileal digestibility is expressed as apparent (AID), standardized (SID), or true (TID) ileal digestibility, depending on how endogenous amino acid losses are considered in the measure of digestibility. The most widely used method to formulate diets and estimate amino acid digestibility is SID.

There are two steps to practically assign SID amino acid values to feed ingredients (Boisen, 1998):

- **Amino acid analysis**: The first step is to submit the feed ingredient to analysis of crude protein and amino acids.
- **Digestibility value**: The second step is to assign SID values to the crude protein and amino acids level in the feed ingredient. The most common approach is to use digestibility values from nutritional tables (NRC, INRA, or the Brazilian Tables), scientific literature, or university databases. Ideally, the digestibility of the same ingredient is used, but ingredients with similar characteristics can also serve as a reference for digestibility.

Assigning phosphorus values

Phosphorus is an inorganic element important for development and maintenance of the skeletal system of swine. Preciseness on assigning the phosphorus value of a feed ingredient is important because supplemental sources of phosphorus are expensive and excess phosphorus increases its excretion in swine waste which imposes a negative effect on the environment.

Phosphorus can be expressed as total, digestible, or available. Available phosphorus represents the amount of phosphorus that is digested, absorbed, and available for utilization according to the slope-ratio method. Total phosphorus represents all phosphorus contained in the ingredient, including non-available phosphorus that is mostly bound to phytate. Digestible phosphorus represents the amount of phosphorus that is digested and absorbed, which is expressed as apparent (ATTD) or standardized (STTD) total tract digestible phosphorus. The basal endogenous losses of phosphorus are accounted for on STTD basis, but not on ATTD basis. The most commonly used method to formulate diets and estimate phosphorus digestibility is STTD.

Similar to the approach used for amino acids, there are two steps to practically assign STTD phosphorus values to feed ingredients (Gonçalves et al., 2017):

- **Phosphorus analysis**: The first step is to submit the feed ingredient to analysis of total phosphorus.
- **Digestibility value**: The second step is to assign STTD value to the phosphorus level in the feed ingredient. The most common approach is to use digestibility values from nutritional tables (NRC, INRA, or the Brazilian Tables), scientific literature, or university databases. Ideally, the digestibility of the same ingredient is used, but ingredients with similar characteristics can also serve as a reference for digestibility. In this case, it is important to pay attention to processing method, amount of phytate, and level of naturally occurring phytase, as these factors influence phosphorus digestibility in feed ingredients. EvaPig® accounts for processing methods and naturally occurring phytase on phosphorus digestibility of feed ingredients, while the NRC does not.

More information about traditional or alternative methods for assigning energy and nutrient values to feed ingredients for swine is found in recent and thorough reviews of literature by Święch (2017), Zhang and Adeola (2017), and Li et al. (2018).

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Feed Sampling and Analysis

Quality of ingredients and complete feeds is essential for effective swine nutrition practices. Analyses to monitor the quality of ingredients and feeds on a regular basis help to avoid errors in estimating nutrient content of ingredients and to identify inaccuracies in feed formulation or feed manufacturing. Moreover, chemical analyses of feed ingredients are important to assign nutritional values to feed ingredients. In order to obtain accurate nutrient values for ingredients and feeds, it is essential to conduct appropriate sampling and analysis.

Sampling procedure

For adequate sampling procedure, it is essential to use proper sampling equipment to ensure the collection of a representative sample (Gonçalves et al., 2016).

Bulk

The most common sampling equipment for bulk feeds or feed ingredients is the slotted grain probe (**Figure 1**), which can be manual or automated. The slotted grain probe should be long enough to reach the bottom of the bulk carrier to obtain a representative sample from top to bottom. Samples should be collected from at least 10 evenly-spaced locations in the bulk carrier (**Figure 2**) to be representative of the entire load of feed or feed ingredient (AAFCO, 2017).

Alternatively, a pelican sampler (**Figure 3)** is also commonly used to steam cut samples during loading or unloading of bulk feeds or feed ingredients. Samples should be collected at least 10 times at regular intervals during loading or unloading (AAFCO, 2017).

In either sampling procedure, the sample size should be at least 1 lb and preferentially 2 lb (AAFCO, 2017).

Bags

The sampling equipment for bagged feeds or ingredients is the bag trier (**Figure 4**). The bag trier should be inserted diagonally in one corner to reach the opposite corner of the bag (**Figure 5)**. At least 10 bags should be collected from the lot, with random selection of bags at varying locations in the lot. The sample size should be at least 1 lb and preferentially 2 lb per bag (AAFCO, 2017).

Liquids

The sampling procedure of liquid ingredients, such as fats, oils, and amino acids, can be performed from bulk, tanks or barrels, or during unloading. The sampling equipment for liquid ingredients in bulk is the bomb sampler and in tanks or barrels is the drum thief sampler. In both cases, liquid ingredients should be stirred before sampling to ensure a proper distribution of nutrients. At least 500 ml or 1 pint of liquid ingredients should be collected from the container (AAFCO, 2017).

Feeders

Samples of complete feed are collected from feeders by probe or hand-grab sampling. Samples collected with a probe have less variability and require fewer number of samples (Jones et al., 2018). Samples should be collected from at least 6 feeders with probe and 9 feeders by hand. Approximately 1 to 2 lb of feed should be collected per feeder and mixed in a composite sample. Creating a composite sample by mixing feed from the sampled feeders is recommended to minimize variability and reduce the number of samples for analysis (Jones et al., 2018).

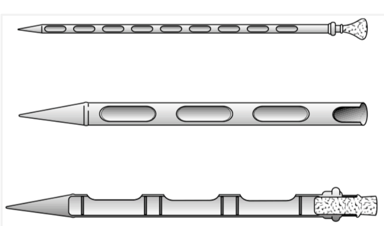

Figure 1. Slotted grain probe (Herrman, 2001)

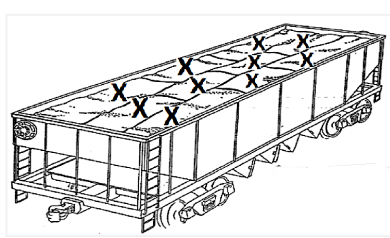

Figure 2. Sampling locations in bulk carriers (AAFCO, 2017)

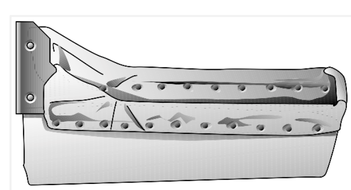

Figure 3. Pelican probe (Herrman, 2001)

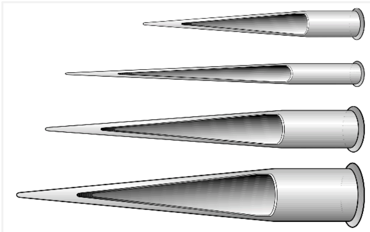

Figure 4. Bag trier (Herrman, 2001)

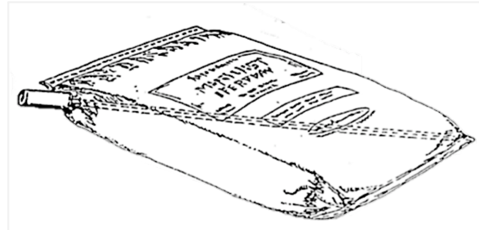

Figure 5. Bag sampling technique (AFFCO, 2017)

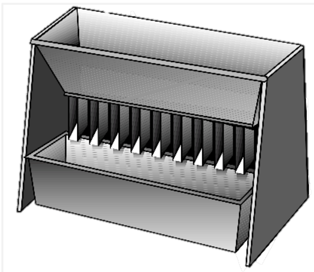

Figure 6. Riffle divider (Herrman, 2001)

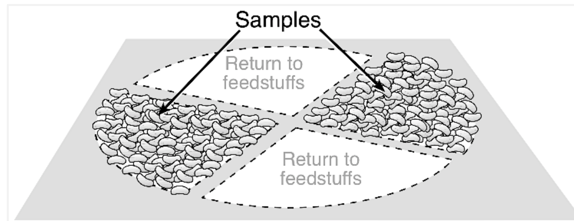

Figure 7. Quartering method (Herrman, 2001)

Preparation of samples for analysis

Sample preparation involves reduction of samples to a suitable size for analysis (Gonçalves et al., 2016). First, composite samples of feeds or ingredients should be mixed thoroughly. Then, samples are split with a riffle divider (**Figure 6**) or by the quartering method (**Figure 7**). The process should yield two samples of approximately 500 g or 1 lb each: one to be submitted for analysis and a second one to be retained as a backup (Herrman, 2001).

Samples for analysis should be placed in plastic or paper bags for submission. Plastic bags are conventionally used, but paper bags are preferred for high-moisture or mold-contaminated samples to prevent condensation of moisture and proliferation of mold growth. Samples should be identified with sample number, date, and content (Herrman, 2001). Labels should not be placed within the bag in contact with the sample (AAFCO, 2017).

Retained samples should be placed in plastic bags, labeled, and immediately frozen for storage. Retained samples should be kept for a predetermined period of time. Usually, the minimum is until feed is consumed by the animals or as long as potential liability exists, e.g. until marketing (Herrman, 2001).

Analysis

The decision on which analyses to perform depends on the individual ingredient and the intended use of the results for either purchasing or diet formulation. In general, analysis of ingredients and feeds often comprises: dry matter (DM), crude protein (CP), ether extract (EE), neutral detergent fiber (NDF), lysine, calcium, and phosphorus. For analysis of highly variable nutrients like calcium, it is recommended to submit multiple samples for analysis and to analyze samples in duplicates (Jones et al., 2018).

Specific analysis for fat and oil quality or mycotoxin concentration should also be considered in some situations.

A list of commercial laboratories performing analyses of complete feeds and feed ingredients and is shown in **List 1**.

Interpretation of analysis results

The analysis results should be interpreted on as-fed, as-is, or as-received basis, but not on dry-matter basis. These values can then be compared with the expected nutrient specifications of ingredients or with the intended nutrient levels in diet formulation (Reese and Thaler, 2010). The analyzed values generally do not match the expected values perfectly because of normal variations associated with sampling and laboratory analyses. The errors associated with sampling can be minimized by following the procedures for sample collection described above. The analytical variation is usually taken into consideration to determine acceptability of feeds and ingredients, which is generally around 15 to 25% in most nutrients (AAFCO, 2018) (**Table 1**).

In cases where the analyzed values do not fall within the expected range after considering the analytical variation, it is recommended to submit the retained sample for a repeat analysis. If the analyzed values are consistent between the first and second analysis, there could be an indication of a problem in diet formulation, feed manufacturing, or sampling, or a variation in ingredient quality or nutrient profile.

Table 1. Determination method and analytical variance for analysis of feed ingredients and feeds

Analysis	Determination method[1]	Analytical variance, %[2, 3]	Concentration range[2]
Proximate analysis			
Ash	942.05	(45 ÷ x) +3	2-88%
Fat	920.39, 954.02, 932.02	10	3-20%
Fiber	962.09	(30 ÷ x) + 6	2-30%
Lysine	975.44	20	0.5-4%
Moisture	934.01, 930.15, 935.29	12	3-40%
Protein	954.01, 976.05, 976.06, 984.13	(20 ÷ x) + 2	10-85%
Protein, pepsin digest	971.09	13	
Protein, NPN	941.04, 967.07	(80 ÷ x) + 3	7-60%
Sugar, total as invert	925.05	12	24-37%
Minerals			
Calcium	927.02, 968.02	(14 ÷ x) + 6	0.5-25%
		10	10-25%
		12	<10%
Cobalt	968.08	25	0.01-0.16%
Copper	925.56	25	0.03-1%
Fluorine	975.08	40	ppm
Iodine	934.02, 935.14	40	ppm
Iron	968.08	25	0.01-5%
Magnesium	968.08	20	0.01-15%
Manganese	968.08	30	0.01-15%
Phosphorus	964.06, 965.17	(3 ÷ x) + 8	0.5-20%
Potassium	975.03, 925.01	15	0.04-8%
Salt	969.10	(7 ÷ x) + 5	0.5-14%
	943.01	(15 ÷ x) + 9	0.5-14%
Selenium	969.06	25	ppm
Sodium	AA	20	0.2-4%
	ICP	15	0.2-4%
Zinc	968.08	20	0.002-6%
Vitamins			
Vitamin A	974.29	30	1,200-218,000 IU/lb
Vitamin B_{12}	952.20	45	
Niacin	961.14, 944.13	25	3-500 mg/lb
Pantothenic acid	945.74	25	4-190 mg/lb
Riboflavin	970.65, 940.33	30	1-1500 mg/lb

[1]Method reference from AOAC (2016).

[2]Analytical variance and concentration range based on AAFCO historic check sample data from AAFCO (2018). The table denotes a true analytical variation and not a tolerance. The values apply both above and below the guarantee and are equally correct.

[3]x = % guarantee. For example, for a 10% protein guarantee the AV, % = (20 ÷ 10) + 2 = 4%. This means the allowed AV is 4% of 10% or ±0.4.

List 1. Commercial laboratories performing analysis of complete feeds and feed ingredients

Barrow-Agee Laboratories
1555 Three Place
Memphis, TN 38116
(901) 332-1590
www.balabs.com

Colorado Analytical Laboratory
P.O. Box 507
Brighton, CO 80601
(303) 659-2313
www.coloradolab.com

Cumberland Valley Analytical Services, Inc.
4999 Zane A. Miller Drive
Waynesboro, PA 17268
(800) CVASLAB
(301) 790-1980
www.foragelab.com

Eurofins Nutrition Analysis Center
2200 Rittenhouse Street Suite 150
Des Moines, IA 50321
(515) 265-1461
www.eurofins.com

Great Plains Analytical Laboratory, Inc.
9503 N Congress Avenue
Kansas City, MO 64153
(816) 891-7337
www.gpalab.com

Midwest Laboratories, Inc.
13611 B Street
Omaha, NE 68144
(402) 334-7770
www.midwestlabs.com

North Dakota State University
Veterinary Diagnostic Laboratory
(mycotoxins only)
NDSU Dept. 7691
P.O. Box 6050
Fargo, ND 58108
(701) 231-7527
(701) 231-8307
www.vdl.ndsu.edu

NP Analytical Laboratories
Checkerboard Square
St. Louis, MO 63164
(800) 423-6832
(314) 982-1310
www.npal.com

Romer Labs, Inc.
(mycotoxins and residues)
130 Sandy Drive
Newark, DE 19713
(302) 781-6400
(302) 781-6378
www.romerlabs.com

SDK Laboratories, Inc. 1000
Corey Road
Hutchinson, KS 67501
(877) 464-0623
(620) 665-5661
www.sdklabs.com

Servi-Tech, Inc.
1816 East Wyatt Earp
P.O. Box 1397
Dodge City, KS 67801
(620) 227-7509
www.servitech.com

Servi-Tech, Inc.
1602 Park West Drive
P.O. Box 169
Hastings, NE 68902
(402) 463-3522
www.servitech.com

Ward Laboratories Inc.
4007 Cherry Ave.
P.O. Box 788
Kearney, NE 68847
(800) 887-7645
(308) 234-2418
www.wardlab.com

Waypoint Analytical, Inc.
2790 Whitten Road
Memphis, TN 38133
(800) 264-4522
(901) 213-2400
www.waypointanalytical.com

This listing is for information purposes only and does not constitute an endorsement of the labs listed nor a discredit to any lab inadvertently omitted from the list.

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Feed Additives in Swine Diets

Feed additives are compounds used in swine diets with the purpose of enhancing performance and health. Many non-antibiotic feed additives have been proposed or evaluated for improving growth performance, regulating gut microbiota, supporting immunity, ameliorating environmental challenges, and enhancing reproductive performance. However, the main challenge with non-antibiotic feed additives is the fact that many have not generated consistent effects or have not been economically justified. A brief overview of non-antibiotic feed additives available for inclusion in swine diets, the proposed mode of action, and the summary of effects on performance are provided in this fact sheet.

Acidifiers

Acidifiers are compounds classified as organic or inorganic acids. Organic acids include formic, fumaric, lactic, benzoic, propionic, and citric acids. Inorganic acids include hydrochloric, sulfuric, and phosphoric acids. Salts of acids also have been used as acidifiers, including calcium-formate, potassium-diformate, sodium-diformate, and sodium-fumarate. Blends of acidifiers are often commercially available because organic and inorganic acids may have a synergistic effect. In addition, some commercial acidifiers contain protected acids that are coated with fatty acids or other molecules, mainly to allow the release of the acid in a targeted location in the gut with the goal to improve effectiveness (Upadhaya et al., 2014).

The mode of action of dietary acidifiers has not been fully understood, but several mechanisms have been proposed. Acidifiers are believed to enhance growth performance via pH reduction in the digestive tract, which improves nutrient digestibility and promotes growth of beneficial bacterial while inhibiting pathogenic bacteria (Jacela et al., 2009a).

Acidifiers have been commonly targeted for weanling pigs. Organic acids have been shown to improve growth performance of weanling pigs more consistently than inorganic acids (Kil et al., 2011; Suiryanrayna and Ramana, 2015; Liu et al., 2018). However, inorganic acids have been often considered as an alternative to organic acids because of lower cost. Acidifiers may also benefit grow-finish pigs (Tung and Pettigrew, 2006), particularly under transition or stressful conditions. In sows, use of acidifiers in the diet improves nutrient digestibility and reduces urinary pH, which aids in controlling the incidence of urinary tract infections (Kluge et al., 2010).

The magnitude and consistency of the responses to acidifiers are variable depending on the nature of acids, inclusion rate, combination of acids, and diet composition (Jacela et al., 2009a). For most acidifiers, the inclusion of excessive levels in the diet affects palatability and decreases feed intake. Also, some acidifiers are corrosive and pose handling and equipment issues during feed manufacturing. Generally, inorganic acids are the most corrosive and salts of acids are the least corrosive acid forms.

Prebiotics

Prebiotics are non-digestible oligosaccharides that can selectively stimulate the growth of beneficial bacterial in the hindgut (Gibson and Roberfroid, 1995). To be consider a prebiotic, the oligosaccharides must be resistant to digestion and absorption, be fermented in the hindgut, and selectively stimulate the growth of non-pathogenic bacteria in the hindgut (Gibson et al., 2004). Bifidobacteria and lactobacilli growth is beneficial for gut health due to short chain fatty acids (SCFA) production. Short chain fatty acids reduce the pH, eliminate enteric pathogens, and also stimulate gut development and integrity. Essentially, prebiotics serve as substrates for fermentation and production of SCFA by beneficial bacteria.

The most common prebiotics are inulin, lactulose, fructo-oligosaccharides, and transgalacto-oligosaccharides, which are considered to be easily fermentable carbohydrates by beneficial bacteria in the hindgut. Prebiotics have been found to be efficient against pathogenic bacteria in pigs (Tran et al., 2016) and most prebiotic effects have been consistent at the gut level (van der Aar et al., 2017). However, results in performance have been inconsistent with use of prebiotics, probably due to differences in stage of production, health status, and husbandry practices (Jacela et al., 2010a; Liu et al., 2018).

Direct-fed microbials

Direct-fed microbials, commonly known as DFM or probiotics, are live microorganisms that, when provided in adequate amounts in the diet, can improve gut microbial balance (Fuller, 1989). Direct-fed microbials are generally categorized into: *Bacillus*-based, lactic acid-producing bacteria, and yeasts (Stein and Kil, 2006).

Bacillus-based DFM are spore-forming bacteria. Spores are thermostable and survive at low pH, which makes *Bacillus*-based DFM stable during feed processing and gastric digestion. *Bacillus*-based DFM produce spores that germinate but do not proliferate in the intestine, which means a constant supply of DFM is required to maintain the microbial population. Lactic acid-producing bacteria are not spore-forming and include *Lactobacillus acidophilus*, *Bifidobacterium bifidum*, and *Enterococcus faecium*. Lactic acid-producing bacteria are able to proliferate in the intestine and sustain a microbial population. However, survival during feed processing is of concern because lactic acid-producing bacteria are not thermostable. Direct-fed microbials are available as a single-species or single-strain product, but most commercial products contain more than one species, strains, and even a combination with yeasts and prebiotics (Liao and Nyachoti, 2017).

Direct-fed microbials, similar to prebiotics, increase the beneficial gut bacterial population mostly by increasing short chain fatty acids (SCFA) production. Short chain fatty acids lower the pH, reduce enteric pathogens, and also stimulate intestinal cell proliferation which maintains gut integrity. The increase in the population of beneficial bacteria also controls enteric pathogens by competitive exclusion. However, the mode of action of DFM seems to be even more comprehensive (Liao and Nyachoti, 2017).

Direct-fed microbials have sometimes been associated with performance improvements when added to swine diets (Zimmermann et al., 2016). Apparently, lactic acid-producing bacteria appear to be more beneficial for weanling pigs to help on gut microbial balance after weaning, whereas *Bacillus*-based DFM seem to be more beneficial for growing-finishing pigs to increase the digestibility of energy and nutrients in high-fiber diets (Liu et al., 2018). However, the effects of DFM in performance are often inconsistent, probably due to the variation in microbial strains, inclusion rate, feeding duration, as well as stage of production, health status, and husbandry practices (Liao and Nyachoti, 2017). Thus, it is difficult to generalize in terms of the effects of DFM on swine diets.

A concern with use of DFM is the transfer of antibiotic resistance genes to pathogenic bacteria (Amachawadi et al., 2018). Commercial DFM products should identify the probiotics to the strain level and ensure the probiotics do not harbor any transferable antibiotic resistance genes.

Yeasts

Yeast cultures are also DFM and the most commonly used in swine diets include *Aspergillus oryzae*, *Candida pintolopesii*, *Saccharomyces boulardii*, and *Saccharomyces cerevisiae*. Yeasts are mainly used as live yeast cultures or yeast derivatives like yeast cell walls. The polysaccharides that constitute the yeast cell walls, notably β-glucans and α-mannans, are believed to be the primary reason for the effects of yeasts (Kogan and Kocher, 2007).

The exact mode of action and properties of yeast cell walls have not been fully understood but are believed to be related to improvements in resistance against enteric infections and modulation of immunity. Yeast cell walls appear to improve gut health by inhibiting colonization of enteric pathogens by blocking their binding sites in gut cells. Yeast cell walls also seem to enhance immunity by stimulation of immune cell function, upregulation of cytokines, and antioxidant activity (Kogan and Kocher, 2007). Another property of yeast cell walls is the toxin-binding capacity, which is mainly explored as mycotoxins adsorbents.

The effects of supplementing diets with yeasts and yeast derivatives on health and performance of pigs are ambiguous. There is evidence to support an improvement in resistance against enteric infections and growth performance of nursery pigs (Shen et al., 2009; Kiarie et al., 2011; Kiros et al., 2018), but these effects are often inconsistent (Liu et al., 2018). In grower-finisher pigs, the effects of yeast on performance have been unremarkable (Keegan et al., 2005; Kerr et al., 2013).

Phytogenics

Phytogenics are plant-derived compounds that include a vast variety of compounds, such as herbs, spices, oleoresins, and essential oils. The composition and concentration of active substances vary widely depending on plant, plant part, geographical origin, harvesting season, storage conditions, and processing techniques (Windisch et al., 2008). The extraction of essential oils is the most predominant plant processing technique. Essential oils contain a mixture of various compounds in different concentrations. The main constituents of essential oils used in swine diets are phenols and terpenes, including anethol, capsaicin, carvacrol, cinnalmaldehyde, curcumin, eugenol, and thymol (Zeng et al., 2015).

The exact mode of action and properties of phytogenics have not been fully understood, but are believed to be mostly related to the antimicrobial action, anti-inflammatory activity, and antioxidant effect of phytogenics. Additionally, phytogenics are often claimed to improve the feed flavor and palatability, which could lead to an increase in voluntary feed intake and growth performance (Windisch et al., 2008), although not well stablished.

The addition of phytogenics to swine diets have sometimes been associated with improvements in performance (Windisch et al., 2008; Zeng et al., 2015). However, the effects of phytogenics on performance have not been consistent (Liu et al., 2018; Soto et al., 2018). There is need for a systematic approach to determine the composition, understand the mode of action, and evaluate the efficiency of phytogenic products. Additionally, safety of phytogenic compounds and potential interactions with feed ingredients and other feed additives warrants further consideration (Jacela et al., 2010a).

Enzymes

Enzymes are active proteins that accelerate the breakdown of specific feed components to release nutrients for digestion and absorption. Enzymes are typically used in swine diets to degrade feed components resistant to endogenous enzymes, inactivate antinutritional factors, and supplement endogenous enzymes that are not present in sufficient amounts (Thacker, 2013). Enzymes typically have designations with the suffix "ase" and are commonly produced by bacteria, fungi, or yeast. The most commonly used enzymes in swine diets are phytase, carbohydrases, and proteases (Jacela et al., 2009b). Phytase is certainly the most widely used among the enzymes due to its efficacy in releasing phosphorus from phytate. Phytase is reviewed in a single topic (Phytase in Swine Diets), while carbohydrases and proteases are detailed here.

Carbohydrases are enzymes that degrade carbohydrates, which include starch and non-starch polysaccharides. Non-starch polysaccharides are components of the cell walls of plant ingredients that are not degradable by the pig, including cellulose, hemicellulose, pectins, α-galactosides, β-glucans, and xylans. Carbohydrases most commonly used in swine diets are β-glucanase and xylanase, but α-amilase, cellulase, pectinase, α-galactosidase, β-mannanase, and others are also commercially available (Thacker, 2013). The use of carbohydrases could provide potential benefits particularly in diets formulated with the addition of ingredients with greater concentration of non-starch polysaccharides, such as barley, wheat, and grain co-products like distillers dried grains with solubles (Jacela et al., 2010c; Jones et al., 2010). Carbohydrases could improve the nutritional value or allow greater inclusion rate of these ingredients in the diet.

Proteases are enzymes that degrade proteins and act on protein-based anti-nutritional factors. Proteases used in swine diets have the ability to degrade a wide range of proteins, including less digestible proteins, such as glycinin and β-conglycinin in soybean meal-based diets (Chen et al., 2017). Proteases are often added to the diet in combination with carbohydrases, but single proteases are also commercially available (Zuo et al., 2015). The use of proteases could provide potential benefits particularly in the nursery, as pigs experience a decrease in enzymatic activity at weaning. Moreover, proteases could aid in the digestion of soybean proteins that are less digestible by weanling pigs and in the degradation of soybean allergens, particularly glycinin and β-conglycinin (Zuo et al., 2015).

Carbohydrases and proteases have often been shown to improve digestibility of nutrients and availability of energy of feed ingredients (Kiari et al., 2007; Emiola et al., 2009; Zuo et al., 2015). Recently, xylanase has been associated with a potential reduction in finisher mortality (Zier-Rush et al., 2016). However, the ability of in-feed enzymes to improve performance has not been proven consistent (Jacela et al., 2009b; Jacela et al., 2010c; Jones et al., 2010; Torres-Pitarch et al., 2017). The inconsistent effects of in-feed enzymes on performance could be due to denaturation of enzymes in the stomach, prompting the use of enzymes that are active over a broad pH range and are resistant to the action of gastric enzymes (Thacker, 2013). Moreover, the type and level of enzymes in a commercial product should match the type and level of substrates present in the feed ingredients included in the diet to achieve a better response to in-feed enzymes. For example, diets based on wheat probably would respond more to added xylanase, while barley would respond more to β-glucanase (Jacela et al., 2009b). Ultimately, the inclusion of enzymes in swine diets needs to be economically justified.

Pharmacological levels of zinc and copper

Zinc and copper are trace minerals required at concentrations of 50 to 110 ppm and 5 to 10 ppm, respectively, to meet the nutrient requirement of pigs. However, the addition of zinc and copper at quantities greater than the requirement exerts a beneficial effect on growth performance of nursery and grow-finish pigs (Liu et al., 2018). Greater quantities of zinc and copper are often referred as growth promoting or pharmacological levels.

Pharmacological levels of dietary zinc between 2,000 and 3,000 ppm is a common recommendation to nursery diets to reduce post-weaning diarrhea and improve growth performance (Hill et al., 2000; Shelton et al., 2011). The maximum tolerable dietary level for swine is generally set at 1,000 ppm with the exception of zinc oxide, which may be included at higher levels (NRC, 2012) for short periods of time immediately after weaning. The grow-promoting effects have been consistently demonstrated with dietary zinc provided as zinc oxide (ZnO) (Hill et al., 2001; Hollis et al., 2005; Walk et al., 2015), while zinc sulfate ($ZnSO_4$) has greater potential to induce toxicity (Hahn and Baker, 1993). Organic sources of zinc with greater bioavailability have not consistently demonstrated the same benefits as zinc oxide when organic zinc is added at lower levels (Hahn and Baker, 1993; Carlson et al., 2004; Hollis et al., 2005). The mode of action of pharmacological levels of zinc to improve growth performance seems to be related to antimicrobial activity, antioxidant capacity, development of gut morphology, and maintenance of gut integrity (Højberg et al., 2005; Zhu et al., 2017). However, pharmacological levels of zinc appear to interfere with calcium and phosphorus absorption, prompting the use of phytase or greater levels of calcium and phosphorus in the diet to ameliorate this effect (Blavi et al., 2017).

Pharmacological levels of dietary copper between 125 and 250 ppm are commonly used in the diet to enhance fecal consistency in nursery pigs and improve growth performance in both nursery and grow-finish pigs (Bikker et al., 2016; Coble et al., 2017). The most commonly used source of dietary copper is copper sulfate ($CuSO_4$) (Cromwell et al., 1998), but tribasic copper chloride (TBCC) is as effective as copper sulfate in promoting growth performance (Cromwell et al., 1998; Coble et al., 2017). Organic sources of copper with greater bioavailability, such as Cu-amino acid chelate, also seem to have the potential to influence growth performance (Pérez et al., 2011; Carpenter et al., 2018). The mode of action of dietary copper to improve growth performance appears to be mainly attributed to antimicrobial activity (Højberg et al., 2005).

A typical recommendation is to use pharmacological levels of zinc in initial nursery diets fed to pigs up to 25 lb and then replace zinc by pharmacological levels of copper for the remaining nursery period. In the grow-finish period, pharmacological levels of copper but not zinc can be used. Additive effects of using pharmacological levels of zinc and copper are not common (Hill et al., 2000), but might occur to some degree (Pérez et al., 2011). In diets with in-feed antimicrobials, the use of pharmacological levels of zinc or copper seems to have an additive effect in growth performance (Stahly et al., 1980; Hill et al., 2001).

The use of pharmacological levels of zinc and copper poses an environmental concern because of the greater excretion of minerals in swine waste and ultimately in the soil fertilized with swine manure (Jondreville et al., 2003). In addition, the implication of pharmacological levels of zinc and copper as a cause of increasing antimicrobial resistance is a rising concern (Yazdankhah et al., 2014). Therefore, regulations have been implemented in some countries restricting or prohibiting the use of zinc or copper as growth promoters. Thus, there is an appeal for prudent use of pharmacological levels of zinc and copper in swine production.

Medium-chain fatty acids

Medium-chain fatty acids (MCFA) are saturated fatty acids with 6 to 12 carbon in length, and are caproic (C6), caprylic (C8), capric (C10), and lauric (C12) acids. Medium-chain fatty acids occur naturally in triglycerides of various feed ingredients, especially coconut oil and palm oil, but are commercially available as single MCFA or blends of MCFA. The characteristics of medium-chain fatty acids include easy digestion and rapid absorption, which makes MCFA a readily available source of energy for the pig (Zentek et al., 2011).

The inclusion of MCFA in swine diets have demonstrated a potential to improve growth performance and gut health particularly in nursery pigs (Zentek et al., 2011; Gebhardt et al., 2017). Medium-chain fatty acids provide a readily available source of energy, which can be utilized by the pig for growth or by the gut cells to improve gut development and integrity (Zentek et al., 2011; Liu, 2015). The effects of MCFA on growth performance are greatly dependent on MCFA type, purity, and inclusion rate in the diet (Gebhardt et al., 2017). Improvements in nursery performance have been demonstrated with 0.50% inclusion of C6 or C8 as well as with 0.25, 0.50, 1.0 or 1.50% inclusion of a 1:1:1 blend of C6, C8, and C10 (Gebhardt et al., 2017).

In addition, MCFA are able to inactivate bacteria and virus (Zentek et al., 2011; Hanczakowska, 2017), contributing to both gut health and feed safety (Liu, 2015; Cochrane et al., 2017; Gebhardt et al., 2018a).

Chromium

Chromium is an essential trace mineral primarily involved in the metabolism of glucose. Chromium potentiates the action of insulin by facilitating the binding of insulin to receptors and thus improving glucose utilization (NRC, 2012). Feed ingredients commonly used in swine diets contain a significant amount of chromium, ranging from 1,000 to 3,000 ppb, but bioavailability is typically low. Organic sources of chromium, such as chromium picolinate, chromium nicotinate, chromium propionate, and chromium yeast, are more bioavailable and more utilized in swine diets than inorganic sources, such as chromium chloride. The use of chromium sources is legally allowed in swine diets up to 200 ppb according to a letter of non-objection from the Food and Drug Administration. Dietary addition of chromium is most often targeted to finishing pigs and sows.

Addition of chromium to diets for finishing pigs has been related to improvements in growth performance and carcass leanness, with no impact on characteristics related to pork quality (Lindemann et al., 1995; Lien et al., 2001; Sales and Jančík, 2011; Gebhardt et al., 2018b). The mechanism of chromium to improve lean deposition is not clear, but it could be due to the stimulation of protein deposition and lipid degradation as a response to insulin activity (Lien et al., 2001). However, the effects of chromium on grow-finish pigs have been modest (Gebhardt et al., 2018b) and not consistent (Mooney and Cromwell, 1999; Shelton et al., 2003; Matthews et al., 2005; Kim et al., 2009). The variation in chromium status of the pig, amount of available chromium in the diet, and environmental conditions could contribute to inconsistency. Due to this variability and inconsistency in performance, there is currently no estimate for chromium requirements for swine (NRC, 2012).

Addition of chromium to diets for sows has been related to an increase in litter size (Lindemann et al., 1995; Lindemann et al., 2004; Wang et al., 2013). The ability of chromium to increase litter size is primarily associated to the influence of insulin and glucose on nutritional status and reproductive hormones of sows before breeding (Cox et al., 1987; Whitley et al., 2002; Woodworth et al., 2007). The magnitude of the effect of chromium on litter size is dependent on dose and feeding duration, but the improvement on sow prolificacy is generally consistent.

Additive effects of supplementation of sow diets with chromium and carnitine have been found on reproductive performance (Real et al., 2008). Both chromium and carnitine influence energy metabolism of sows but through different mechanisms that seem to act synergistically (Woodworth et al., 2007). The supplementation of sow diets with chromium and carnitine has been shown to additively improve farrowing rate and thus number of piglets born alive (Real et al., 2008).

Carnitine

Carnitine is a vitamin-like compound involved in the transport of fatty acids into the mitochondria to produce energy. Carnitine is synthesized from lysine and methionine and derived from the diet (Fischer et al., 2009). Only the L-isomer of carnitine is active for swine. Dietary addition of carnitine is most often targeted to grow-finish pigs and sows.

Addition of carnitine in grow-finish diets has been shown to improve growth performance and carcass leanness (Owen et al., 2001a; James et al., 2013a; Ying et al., 2013). The effects of carnitine in grow-finish pigs have been attributed to an enhancement in the ability to efficiently use fat for energy and to synthesize amino acids and proteins (Owen et al., 2001b). To the pig, this translates into improved growth rate and efficiency, decreased lipid deposition, and increased protein accretion (Heo et al., 2000). However, the effects of carnitine in grow-finish pigs have been inconsistent (Owen et al., 2001a,b; Pietruszka et al., 2009; James et al., 2013b). It's been suggested that factors that affect energy intake, such as stocking density, health status, and environmental temperature, as well as the amino acid levels in the diet could influence the effects of carnitine in grow-finish pigs (Ying et al., 2013).

Addition of carnitine to diets for sows has been shown to increase birth weight and weaning weight of piglets and litters (Musser et al., 1999; Ramanau et al., 2004; Ramanau et al., 2008; Wei et al., 2018). Carnitine has also been shown to improve litter size and reduce the number of stillborn or non-viable piglets (Musser et al., 1999; Eder et al., 2001; Ramanau et al., 2004; Zhang et al., 2018), although less consistently. There are many mechanisms by which carnitine acts to increase birth weight, but are mainly involved with improvement of nutrient supply and muscle development of fetus via increased concentration of insulin-like growth factors (IGF-1 and IGF-2), enhanced placental development, and improved supply of glucose via placenta (Doberenz et al., 2006; Woodworth et al., 2007; Brown et al., 2008; Eder, 2009; Zhang et al., 2018). In addition, there are other mechanisms by which carnitine acts to increase weaning weight, which are mainly involved with improvement in milk production, milk composition, and suckling behavior (Ramanau et al., 2004; Birkenfeld et al., 2006; Zhang et al., 2018). Recently, carnitine has been associated with enhancement of the antioxidant status of sows and piglets (Wei et al., 2018).

Additive effects of supplementation of sow diets with carnitine and chromium have been found on reproductive performance (Real et al., 2008). Both carnitine and chromium influence energy metabolism of sows but through different mechanisms that seem to act synergistically (Woodworth et al., 2007). The supplementation of sow diets with carnitine and chromium has been shown to additively improve farrowing rate and thus number of piglets born alive (Real et al., 2008).

Betaine

Betaine is an amino acid derivative that serves as a methyl donor in metabolic processes. Betaine provides methyl groups (—CH_3) for the synthesis of many compounds, such as creatine and carnitine, and decrease the requirement for other methyl donors, such as methionine and choline. Betaine is also an osmotically active compound that regulates water movement and electrolyte balance, providing osmotic protection for many cells, including intestinal cells and muscle fibers (Eklund et al., 2005). Betaine can be produced by chemical synthesis or as a by-product of sugarbeet processing. Betaine is commercially available as anhydrous betaine, betaine monophosphate, and betaine hydrochloride (Eklund et al., 2005).

Addition of betaine to grow-finish diets has been demonstrated to improve growth performance, carcass leanness, and pork quality (Matthews et al., 2001a,b), but the effects of betaine have been inconsistent (Sales, 2011). The mode of action of betaine have not been fully understood, but it has been suggested that betaine may have an energy-sparing effect that improves growth and protein deposition (Schrama et al., 2003) and an osmo-protectant effect that improves pork quality (Eklund et al., 2005). The osmo-protectant capacity of betaine may also improve nutrient digestibility and gut health (Eklund et al., 2005), and enhance the ability of grow-finish pigs to cope with heat stress (Mendoza et al., 2017a,b).

Addition of betaine to sow diets has been demonstrated to potentially improve reproductive performance, but there is little evidence to support consistent effects (Ramis et al., 2011; van Wettere et al., 2013). There is growing interest to supplement betaine in sow diets during summer (van Wettere et al., 2012, Cabezón et al., 2016; 2017). Betaine is believed to improve lactation feed intake, reduce wean-to-estrus interval, and enhance embryo survival during heat stress (van Wettere et al., 2012, Cabezón et al., 2016). It’s been suggested that betaine may ameliorate the effect of heat stress on sows due to an energy-sparing effect that improves energy utilization and an osmo-protectant effect that increases water retention and regulates electrolyte balance (Cabezón et al., 2016). However, the benefits of betaine supplementation on reproductive performance of sows require further research before a definitive recommendation can be made.

Conjugated linoleic acid

Conjugated linoleic acid (CLA) is a term for isomers of linoleic acid (C18:2). The function of CLA involves regulation of body composition and energy retention (Müller et al., 2000).

Addition of CLA to grow-finish diets has been related to improvements in growth performance, carcass leanness, and fat firmness (Eggert et al., 2001; Thiel-Cooper et al., 2001; Larsen et al., 2009). The mode of action of CLA involves the regulation of enzymes and gene expression in lipid metabolism (Jiang et al., 2010). Also, CLA increases the proportion of saturated to unsaturated fatty acids in fat, which leads to greater fat firmness (Larsen et al., 2009). There is a nutritional opportunity for addition of CLA to grow-finish diets to offset the issues of fat softness and iodine value that arise from diets with unsaturated fatty acid sources, such as diets with distillers dried grains with solubles (White et al., 2009).

Another potential benefit of feeding CLA to grow-finish pigs is the incorporation of CLA in pork products (Dugan et al., 2004). Conjugated linoleic acid-rich pork products have been shown to provide health benefits and may have an appeal to consumers.

Kapok oil

Kapok oil is extracted from seeds of kapok (*Ceiba pentandra*), a tropical tree. Kapok oil is rich in cyclopropenoid fatty acid, which is able to reduce desaturation of fatty acids and thus increase saturated fatty acids in oils (Yu et al., 2011; Anwar et al., 2014). Addition of kapok oil to diets for grow-finish pigs has been related to improvements in pork fat firmness (Maeda et al., 2017). Similar to conjugated linoleic acid, there is a nutritional opportunity for the addition of kapok oil to grow-finish diets to offset the issues of fat softness and iodine value that arise from diets containing high concentrations of unsaturated fatty acids from ingredients such as distillers dried grains with solubles or vegetable oils.

Ractopamine

Ractopamine hydrochloride is a phenethanolamine β-adrenergic agonist that redirects nutrients away from fat deposition and towards lean deposition. The mode of action of ractopamine primarily involves the modulation of metabolic pathways and signals in muscle and lipid cells to enhance protein accretion. Other mechanisms also include regulation of hormone release and modification of blood flow (Mersmann, 1998).

Ractopamine inclusion in finishing diets has been consistently related to improvements in growth rate, feed efficiency, and carcass leanness with minimal effects on pork quality (Apple et al., 2007; Bohrer et al., 2013). Ractopamine seems to enhance lean gain by partitioning energy towards protein deposition, which also improves efficiency because protein requires less energy to be deposited than fat (Mersmann, 1998). The effects of ractopamine progressively decrease over time as prolonged exposure to β-adrenergic agonist causes desensitization of receptors (Mersmann, 1998). Also, the effects of ractopamine are lost once the inclusion of ractopamine in the diet is stopped.

Ractopamine is labeled for addition to finishing diets at 5 to 10 mg/kg for the last 45 to 90 lb of gain before marketing, which is about 21 to 35 days. Ractopamine should be continuously supplied up to marketing as the beneficial effects of ractopamine are quickly lost after withdrawal. Also, appropriate nutritional adjustments must be made when adding ractopamine in finishing diets to support greater rate of lean gain. It is legally required that diets with ractopamine contain at least 16% crude protein. It is recommended to increase lysine levels by 5 to 6 g of SID Lys per day (0.2 to 0.25 percentage units of SID Lys) while maintaining other amino acids at a proper ratio to lysine (Jacela et al., 2009b).

Use of ractopamine has raised concerns regarding swine welfare, particularly on behavior, ease of handling, susceptibility to stress, and incidence of fatigued, non-ambulatory market-weight pigs (Marchant-Forde et al., 2003). Finishing pigs fed ractopamine have been found to be more difficult to handle and more susceptible to fatigue and stress with aggressive handling, especially at high inclusion of ractopamine (James et al., 2013c; Ritter et al., 2017). Implementation of low stress handling and transportation practices is particularly important with pigs fed ractopamine in order to safeguard welfare and minimize losses.

Antioxidants

Antioxidants are compounds that reduce the oxidative degradation of fatty acids, i.e. fats and oils. Antioxidants thus can be added to fats and oils to reduce oxidation of fats and oils. However, antioxidants cannot reverse fat oxidation once it occurs (Kerr et al., 2015).

Antioxidants are classified by mode of action into primary and secondary antioxidants based on effects on which stage of fat oxidation. Fat oxidation is described in three stages: initiation, propagation, and termination, with different compounds produced in each stage (Shurson et al., 2015). Primary antioxidants inhibit the initiation and delay the propagation of fat oxidation, and are most effective in the early stages of oxidation. Primary antioxidants are natural carotenoids, flavonoids, tocopherols, and synthetic ethoxyquin, butylated hydroxytoluene (BHT), butylated hydroxyanisole (BHA), propyl gallate, among others (Kerr et al., 2015). Secondary antioxidants slow the rate of fat oxidation and are effective in different stages of oxidation. Secondary antioxidants are citric acid and ethylenediamine-tetra-acetic acid (EDTA), among others (Kerr et al., 2015). Commercial antioxidant products commonly include a combination of antioxidants with synergistic activity to improve efficacy (Jacela et al., 2010b).

Antioxidants have been used to ameliorate the impact of fat oxidation on growth performance (Lu et al., 2014), although the benefits have not been consistent (Song et al., 2014). Also, antioxidant addition in swine diets have been used to control rancidity, which could help to maintain palatability and prolong storage time (Kerr et al., 2015). In that sense, the use of antioxidants may be more important in diets with high amounts of added fat and diets manufactured in warm climates (Jacela et al., 2010b). Regular analysis of fat sources important to provide an accurate assessment of the degree of fat oxidation and rancidification.

Mycotoxin binders

Mycotoxins are toxic compounds produced by mold growth in feed ingredients. The most significant mycotoxins affecting swine are aflatoxin, vomitoxin, zearalenone, fumonisin, and ochratoxin, which are produced by molds that belong to the genera *Aspergillus*, *Fusarium*, and *Penicillium*. Mycotoxin contamination prevention includes pre- and post-harvest strategies. Interventions carried out in the field to prevent fungal infestation, such as crop rotation, tillage, insect control, and fungicides, are the most effective but often insufficient to prevent mycotoxin contamination (Jard et al., 2011). After harvest, one effective intervention is to screen and clean grain to reduce mycotoxin contamination in grains (Yoder et al., 2017). The most prevalent intervention is the inclusion of mold inhibitors and mycotoxin binders in the feed (Vila-Donat et al., 2018).

Mold inhibitors are used to control mold contamination and prevent mold growth in order to minimize the risk of having proliferation of mycotoxin-producing molds in grain or feed (Jacela et al., 2010b). Acidifiers are commonly used as mold inhibitors, particularly organic acids such as propionic acid. Acidifiers display fungicidal properties by reducing the pH in grain and feed (Suiryanrayna and Ramana, 2015). However, the use of acidifiers as mold inhibitors have no effect on mycotoxins already present in contaminated grain and feed (Jacela et al., 2010b).

Mycotoxin binders or adsorbents are substances that bind to mycotoxins and prevent absorption through the gut (**Table 1**). The most commonly used mycotoxin binders in swine feeds are aluminosilicate binders, which include clays, bentonites, zeolites, and hydrated sodium calcium aluminosilicate (HSCAS). The aluminosilicate binders are natural, inorganic mycotoxin binders containing a porous structure made of silica that is able to adsorb and trap mycotoxins (Jouany, 2007; Di Gregorio et al., 2014). The aluminosilicate binders are very effective aflatoxin binders, but have limited activity against other types of mycotoxins (Huwig et al., 2001; Jiang et al., 2012; Vila-Donat et al., 2018). Furthermore, aluminosilicate binders are nonspecific and bind vitamins and trace minerals as well (Huwig et al., 2001; Vila-Donat et al., 2018).

Other mycotoxin binders used in swine feeds are yeast components. The yeast components are natural, organic mycotoxin binders extracted from the cell walls of *Saccharomyces cerevisiae*, primarily α-mannans and β-glucans (Jouany, 2007). The yeast components have a diverse mechanism of adsorption and act against a wide range of mycotoxins (Huwig et al., 2001). Furthermore, organic yeast components are biodegradable and do not accumulate in the environment after being excreted in the manure, in contrast to inorganic silicate binders (Jouany, 2007).

However, mycotoxin binders are vastly ineffective against vomotoxin (Dänicke, 2002; Döll and Dänicke, 2003; Frobose et al., 2015). Vomitoxin is the colloquial term for deoxynivalenol (DON), the most common contaminant of grains and feed (Rodrigues and Naehrer, 2012). Recently, sodium metabisulfite has been found to be a promising agent against vomitoxin (Frobose et al., 2017; Shawk et al., 2018). Although not approved by Food and Drug Administration as a DON-detoxifying agent, sodium metabisulfite reacts with DON to form a non-toxic component in a process that requires heat and humidity for optimal efficiency (Young et al., 1987). The addition of sodium metabisulfite to diets naturally contaminated with vomitoxin seems to restore feed intake and improve growth performance of nursery pigs (Frobose et al., 2017; Shawk et al., 2018). However, sodium metabisulfite is known to degrade the vitamin thiamin, which needs to be supplemented in diets with sodium metabisulfite.

Table 1. Effective mycotoxin binders based on efficacy demonstration in pigs

Mycotoxin type	Effective mycotoxin binder
Aflatoxins	Aluminosilicates/Bentonites[1]
Vomitoxin (DON)	Sodium metabisulfite[2]
Zearalenone	Limited efficacy data with Aluminosilicates/Clays[3]
Fumonisins	Lacking consistent efficacy data
Ochratoxin A	Lacking consistent efficacy data

[1]From Harper et al. (2010).
[2]From Frobose et al. (2017) and Shawk et al. (2018).
[3]From Jiang et al. (2012).

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Phytase in Swine Diets

Phytate is the primary storage of phosphorus in feedstuffs of plant origin. However, phytate-bound phosphorus is mostly unavailable to pigs, with digestibility in the range of 20 to 30%. Phytase is an enzyme that acts on phytate to release phosphorus in a form available to pigs. Phytate also forms complexes with protein and minerals, preventing nutrient absorption. The strategic use of phytase in swine diets to improve phosphorus digestibility and reduce the antinutritional effects of phytate is discussed in this fact sheet.

Phytate

Phytic acid is the primary storage of phosphorus in plants, typically in the form of phytate and contributing to 60 to 80% of phosphorus in feedstuffs of plant origin (Eeckhout and De Paepe, 1994). Phytate consists of an inositol bound to six phosphates and contains approximately 28% phosphorus. Corn-soybean meal-based swine diets typically contain 1% phytate or 0.28% phytate-bound phosphorus, but the level varies with the ingredients in the diet.

Phytate is considered an antinutritional factor for swine because it reduces digestibility of phosphorus, energy, and other nutrients in pigs. The antinutritional effect of phytate on phosphorus availability is a consequence of pigs not being able to effectively release phosphorus from phytate. Phytate becomes negatively charged in the digestive tract of pigs, which confers phytate the capacity to form stable complexes with protein and minerals like calcium, zinc, and iron in the digestive tract, preventing nutrient absorption (Woyengo and Nyachoti, 2013). Therefore, the degradation of phytate in the upper part of the digestive tract is essential to improve phosphorus availability and eliminate the antinutritional effects of phytate.

Phytase

Phytase is an enzyme that catalyzes the release of phosphorus from phytate. The sources of phytase with respect of swine nutrition are: endogenous phytase produced in the small intestine, microbial phytase produced in the large intestine, intrinsic plant phytase derived from feedstuffs, and exogenous microbial phytase added to the diet (Humer et al., 2015). The endogenous phytase activity is negligible in swine and the intrinsic phytase activity in feedstuffs is variable, with corn and soybean typically containing minor phytase activity (Eeckhout and De Paepe, 1994). Consequently, only 20 to 30% of phosphorus bound to phytate is released by the action of these phytase sources (Adeola and Cowieson, 2011).

The addition of exogenous microbial phytase to swine diets is a common practice to efficiently and economically enhance phosphorus release from phytate (Selle and Ravindran, 2008). The effects of exogenous microbial phytase follow a curve of diminishing returns, with most of the beneficial effects generated within the dose of phytase necessary to destroy 30 to 40% of the dietary phytate and proportionately lower effects thereafter (Cowieson et al., 2017).

Exogenous microbial phytases are typically derived from bacteria or fungi, such as *Escherichia coli*, *Aspergillus niger*, *Peniophora lycii*, and *Buttiauxella* spp. (Selle and Ravindran, 2008). These microbial phytases are divided into 3- and 6-phytases according to site of action on phytate, and into first or new generation depending on generation of development. All commercially available microbial phytases for swine are classified as acidic phytases, with optimal activity at pH of 2.5 to 5.5 (Humer et al., 2015). **Table 1** presents the characteristics of some of the current commercial phytase sources for swine.

Phytase activity

Phytase activity is expressed as phytase units (FTUs or FYTs). One FTU is officially the amount of phytase required to liberate 1 mmol of inorganic phosphate per minute from 0.0051 mol/L sodium phytate at pH 5.5 and temperature of 37°C (AOAC, 2000).

Table 1. Characteristics of some of the currently commercially available phytase sources for swine

Trade name	Supplier	Type[1]	Protein origin	Expression	Optimal pH[2]	Maximal temperature[3]
Axtra® PHY TPT	DuPont	6-phytase	*Buttiauxella* spp.	*Trichoderma reesei*	3.0	203°F
Natuphos® E G	BASF	6-phytase	*Hafnia* sp.	*Aspergillus niger*	2.0 and 5.0-5.5	203°F
OptiPhos® CT	Huvepharma	6-phytase	*Escherichia coli*	*Pichia pastoris*	3.5 and 5.0	185°F
Quantum® Blue G	AB Vista	6-phytase	*Escherichia coli*	*Trichoderma reesei*	3.5-5.0	194°F
Ronozyme® Hiphos GT	DSM	6-phytase	*Citrobacter braakii*	*Aspergillus oryzae*	3.0-4.5	203°F

[1]Initial site of action of phytase on phytate.
[2]Based on *in vitro* assays. Adapted from Dersjant-Li et al. (2014).
[3]Maximal recommended temperature for heat-stable forms of the products only.

Phytase efficacy

The efficacy of phytase varies with phytase characteristics, which are determined based on phytase origin (bacterial or fungal phytase), phytase generation (first or new generation), and site of action of phytase on phytate (3- or 6-phytase, referring to the initial carbon site of hydrolysis on phytate). The most important characteristics influencing phytase efficacy include activity in the upper digestive tract, affinity to phytate, and resistance to degradation.

Characteristics influencing phytase efficacy

- **Activity in the upper digestive tract**: The degradation of phytate in the upper part of the digestive tract (stomach and upper small intestine) is essential to improve phosphorus availability and eliminate the antinutritional effects of phytate (Dersjant-Li et al., 2014). The optimal pH range of phytase provides an indication of phytase activity in the upper part of the digestive tract. The pH in the pigs' empty stomach is normally 2.0 to 2.5 and gradually increases to 3.5 to 4.0 with feed, whereas the pH in the pig's upper small intestine is around 4.0 to 6.0 (Pagano et al., 2007). The optimal pH for phytase activity typically varies over a range of 2.5 to 5.5.
- **Affinity to phytate**: The most effective phytases have great affinity to phytate and are able to target phytate at low concentration and from many feedstuff sources (Dersjant-Li et al., 2014).
- **Resistance to degradation**: As phytase is a protein that can be degraded by enzymes in the digestive tract, the most effective phytases are resistant to degradation by enzymes in the digestive tract (Dersjant-Li et al., 2014).

Dietary factors influencing phytase efficacy

Beyond the phytase characteristics, several factors influence the efficacy of phytase, including the amount of phytate in the diet, the amount of phytase added to the diet, and diet formulation. Although it is not clear to which extent diet formulation affects phytase efficacy, it is important to understand the dietary factors that influence the activity of phytase.

- **Feedstuffs**: There is considerable variation in the susceptibility of phytate to phytase depending on feedstuff. Also, the amount of intrinsic phytase varies with feedstuff, with wheat containing more intrinsic phytase than corn, for example (Selle and Ravindran, 2008).
- **Ratio of phytase to phytate**: The ideal ratio of phytase to phytate allows for maximum release of phosphorus from phytate. However, in most of the cases, either phytase or phytate levels are limiting. When phytase is the limiting factor, the release of phosphorus improves with addition of more phytase. When phytate is the limiting factor, the release of phosphorus occurs until all phytate is depleted by phytase but does not improve with further addition of phytase (Cowieson et al., 2016).

- **Inorganic sources of calcium and phosphorus**: The use of high concentrations of inorganic sources of calcium and phosphorus interfere in phytase efficacy. Sources such as limestone and monocalcium phosphate have the potential to increase gut pH, which affects phytase activity and reduces phytate solubility (Dersjant-Li et al., 2014).
- **Calcium level and Ca:P ratio**: Diets formulated with high calcium levels and wide calcium:phosphorus ratios will lower phytase efficacy. Calcium forms a complex with phytate which reduces phytate susceptibility to phytase activity (Selle et al., 2009).
- **Pharmacological levels of zinc**: Diets formulated with pharmacological levels of zinc have lower phytase efficacy. Similar to calcium, zinc forms a complex with phytate which reduces phytate susceptibility to phytase activity (Selle and Ravindran, 2008).

Phytase stability

The stability of phytase under storage and during feed processing determines the ultimate value of phytase as much as its efficacy. There are many factors influencing phytase stability, including thermostability, coating, storage form, storage temperature, storage duration, and feed processing (**Table 2**).

Thermostability and coating

Phytase is susceptible to denaturation by excessive temperature during storage and feed processing. Phytase thermostability can be achieved through coating application to provide protection to phytase or through genetic modification to make phytase intrinsically thermostable. Heat-stable phytase is able to withstand high temperatures under storage and application of heat during pelleting compared to non-heat-stable phytase (Slominski et al., 2007).

Moreover, coating also provides protection to phytase against environmental insults. Coated phytase is able to counteract some of the adverse effects of premix components, high storage temperature, and long storage duration, compared to uncoated phytase (Sulabo et al., 2011).

Storage form

Phytase can be stored in pure form or in a mixture with vitamins or vitamin and trace minerals. Phytase activity is lost to greater extent in premixes containing vitamins and trace minerals than in premixes containing only vitamins (Sulabo et al., 2011; De Jong et al., 2016). The interaction of phytase with premix components seems to affect phytase stability, with inorganic trace minerals appointed as the most likely components to interact with phytase (Shurson et al., 2011). Storage of phytase in pure form is the best means to optimize phytase stability and minimize loss of phytase activity during storage (Sulabo et al., 2011; De Jong et al., 2016).

Storage temperature

Phytase is exposed to varied temperatures and humidity during storage depending on location and season. Storage under conditions of high temperature and humidity, i.e. at 99°F and 75% humidity, considerably reduces phytase activity (Yang et al., 2007; Sulabo et al., 2011). Freeze storage at -4°F also reduces phytase activity (De Jong et al., 2016). In general, storage at room temperature (73°F) or 39 to 73°F at low humidity is ideal to optimize phytase stability and maximize phytase activity during storage (Sulabo et al., 2011; De Jong et al., 2016).

Storage duration

Phytase is stored for varying lengths of time depending on inclusion rate and feed mill volume. Phytase activity gradually decreases with an increase in storage duration, but both storage form and storage temperature influence the rate of degradation during storage (Sulabo et al., 2011; De Jong et al., 2016). In general, storage of phytase for less than 90 to 120 d in pure form or less than 60 d in a premix optimizes phytase stability (De Jong et al., 2016).

Feed processing

The most commonly adopted feed process in swine diets that affects phytase stability is pelleting. Pelleting conditions vary depending on equipment and diet, but normally consist of conditioning temperatures ranging from 149 to 203°F. Phytase activity gradually decreases with an increase in conditioning temperature above 149°F, even with use of heat-stable phytase (De Jong et al., 2017). Alternatively, post-pelleting application of liquid phytase onto pellets is one strategy to maintain phytase stability (Gonçalves et al., 2016).

Table 2. Recommendations to improve phytase stability

Factor	Recommendation
Thermostability	Use heat-stable phytase if pelleting feed or excessive temperature during storage
Coating	Use coated phytase if mixed in a premix or long storage duration (more than 60 to 90 d)
Storage form	Store in pure form
Storage temperature	Store at room temperature or 39 to 73°F at low humidity
Storage duration	Store for less than 90 to 120 d in pure form or less than 60 d in a premix
Feed processing	Use heat-stable phytase if pelleting feed or post-pelleting application of liquid phytase onto cool pellets. Test phytase activity using conventional processing conditions.

Extra-phosphoric effects of phytase

The effects of phytase beyond phosphorus release are termed 'extra-phosphoric' effects of phytase. The primary effect of phytase is the improvement of phosphorus availability through the release of phosphorus from phytate. However, phytate also forms stable complexes with proteins and minerals like calcium, zinc, and iron in the digestive tract and prevents nutrient absorption (Woyengo and Nyachoti, 2013). Thus, the extra-phosphoric effects of phytase are related to the improvement of digestibility of energy, amino acids, and minerals through the dissociation of such complexes (Selle and Ravindran, 2008).

The extra-phosphoric effects of phytase provide economic advantages in diet formulation and enhance the value of dietary phytase. The matrix values for calcium release in a digestible calcium basis seems to be similar to the digestible phosphorus release. However, the assignment of matrix values for other minerals and amino acids should be adopted with caution (Cowieson et al., 2017), as the effects are more variable and have not been fully elucidated (Adeola and Cowieson, 2011). Particularly in the case of amino acids, there is evidence to support the use of amino acids matrix values, but because the effects are not as obvious or consistent it is appropriate to use a more conservative approach (Cowieson et al., 2017).

The use of phytase above conventional levels (500 to 1,000 FTU/kg) seems to have the potential to improve growth performance beyond what is expected with adequate phosphorus levels (Zeng et al., 2014). The exact mode of action of high phytase levels remains unknown, but it is believed to be related to extra-phosphoric effects due to greater degradation of phytate (Adeola and Cowieson, 2011; Cowieson et al., 2011). The greater degradation of phytate removes most of the antinutritional effects of phytate, further improving digestibility of energy, amino acids, and minerals (Selle and Ravindran, 2008). Moreover, the complete degradation of phytate releases *myo*-inositol, a vitamin-like compound with many metabolic functions (Laird et al., 2018; Moran et al., 2018).

The use of high levels of phytase appears to have potential for a greater effect on nursery pig performance (Zeng et al., 2014; Gourley et al., 2018; Laird et al., 2018), with less evidence for effect on grow-finish pig performance (Holloway et al., 2016; Miller et al., 2016; She et al., 2018). Moreover, the effects of high phytase levels appear to be greater if the levels of phosphorus, calcium, and other minerals are marginal in the diet (Zeng et al., 2014; Miller et al., 2016; Laird et al., 2018). Also, it has been suggested that the effects of high phytase levels follow a curve of diminishing returns, with most of the beneficial effects generated within the dose of phytase necessary to destroy 30 to 40% of the dietary phytate and proportionately lower effects thereafter (Cowieson et al., 2017).

Comparison of phytase sources

Several phytase sources are commercially available for use in swine diets. Because of differences in phytase characteristics and variation in recommended levels for similar phosphorus release among products, there is an interest to be able to effectively compare phytase sources (Jones et al., 2010). An approach for comparing different phytase sources is to compare the phytase activity needed to reach a particular available phosphorus or standardized total tract digestible phosphorus release value. This allows for products to be compared on the same level of activity to determine replacement rates for each phytase source (Gonçalves et al., 2016). **Table 3** presents the release values for comparison of some of the current commercial phytase sources using this approach. A phytase calculator has also been developed for these commercial phytase sources (KSU Phytase Calculator).

Moreover, analytical techniques used to determine phosphorus release values are variable among commercial phytase manufacturers (Jacela et al., 2010). Because of this, the amount of phosphorus released per unit of phytase differ between phytase products. The standard method is the AOAC assay (AOAC, 2000), but some phytase suppliers modify this method according to different phytase characteristics.

Table 3. Levels of dietary phytase to achieve the phosphorus release values with some of the commercially available phytase sources

Available phosphorus release (%)	Digestible phosphorus release (%)[2]	Dietary phytase levels (FTU/kg of complete diet)[1]				
		Axtra® PHY	Natuphos® E	OptiPhos®	Quantum® Blue G	Ronozyme® Hiphos
0.09	0.08	300	300	180	180	300
0.10	0.09	350	350	210	210	350
0.11	0.10	400	400	230	230	400
0.12	0.11	500	500	290	290	500
0.13	0.11	600	600	350	350	600
0.14	0.12	750	750	430	430	750
0.15	0.13	900	900	520	520	900
0.16	0.14	1150	1150	660	660	1150

[1]Values are derived from data supplied by the phytase suppliers: Axtra® PHY (DuPont, Wilmington, Delaware), Natuphos® E (BASF, Florham Park, New Jersey), OptiPhos® (Huvepharma, Peachtree City, Georgia), Quantum® Blue G (AB Vista, Marlborough, UK), Ronozyme® Hiphos (DSM, Parsippany, New Jersey).

[2]Standardized total tract digestible phosphorus release calculated using a conversion from available phosphorus of 88%, using monocalcium phosphate as a reference.

Phytase product inclusion

The amount of phytase product that needs to be included in swine diets to achieve the dietary phytase level goal can be calculated by the following:

Dietary phytase level goal, FTU/kg ÷ Phytase product concentration, FTU/g = Phytase product inclusion, g/kg

Phytase product inclusion, g/kg × 907.2 kg/ton = Phytase product inclusion, g/ton of complete diet

Phytase product inclusion, g/ton ÷ 453.6 g/lb = Phytase product inclusion, lb/ton of complete diet

For example, consider the goal is to achieve 200 FTU/kg of phytase in the diet and the phytase product contains 2500 FTU/g. Using the calculations described above, the amount of phytase product that needs to be included in the diet is 0.16 lb/ton, as follows:

200 FTU/kg ÷ 2500 FTU/g = 0.08 g/kg phytase product inclusion

0.08 g/kg × 907.2 = 72.6 g/ton phytase product inclusion

72.6 g/ton ÷ 453.6 g/lb = 0.16 lb/ton phytase product inclusion

Phytase calculator

A phytase calculator has been developed to determine the levels of dietary phytase for some of the commercially available phytase sources and the amount of phytase product to be included in swine diets (KSU Phytase Calculator).

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Mycotoxins in Swine Diets

Mycotoxins are toxic compounds produced by mold growth in feed ingredients. Although not all molds produce toxins, the most significant mycotoxins affecting swine are aflatoxin, vomitoxin, zearalenone, fumonisin, and ochratoxin. These mycotoxins are produced by molds that belong to the genera *Aspergillus*, *Fusarium*, and *Penicillium*. The occurrence of mycotoxins in swine diets is discussed in this fact sheet.

Mycotoxin formation

Mycotoxins are only produced by certain molds and under certain conditions (**Table 1**). Thus, the presence of molds in feedstuffs or feeds does not automatically imply presence of mycotoxins. The major factors influencing mold growth and mycotoxin formation are moisture and temperature. Mold growth requires readily available starch from grains, moisture, air, and appropriate temperatures, often 54 to 77°F. Mycotoxin formation can occur under such conditions, but typically the presence of stressors, such as drought, high environmental temperatures, excessive water, nutrient deficiency, insect damage, and harvest damage, are also necessary to predispose the formation of mycotoxins (Osweiler and Ensley, 2012; Rodrigues and Naehrer, 2012).

Mycotoxin-producing molds are classified into two categories: field and storage molds (Osweiler and Ensley, 2012). Field molds grow in grains before harvest and require high relative humidity above 70% and typically grain moisture above 22% for growth. The most concerning field molds are the *Fusarium* species, which produce vomitoxin, zearalenone, and fumonisin. Storage molds grow in grains after harvest and during storage of grains and feeds. These molds do not require high humidity and even grow in grains with 12 to 18% moisture. Storage molds include *Aspergillus* and *Penicillium* species, which produce aflatoxin and ochratoxin. However, under certain conditions, storage molds grow in grains even prior to harvest and field molds continue to grow during storage. This is often the case of *Aspergillus flavus*, a mold that produces aflatoxin. Moreover, grains and feeds may contain more than one mold and have a number of mycotoxins present at the same time.

Mycotoxin contamination

Mycotoxin contamination occurs worldwide. Certain regions are predisposed to have higher risk of mycotoxin contamination. For example, temperate regions tend to have higher field mold prevalence (*Fusarium* species), whereas tropical and subtropical regions have higher storage mold prevalence (*Aspergillus* and *Penicillium* species). When conditions are favorable for field molds, grains from a geographic location are widely affected by mycotoxins. In contrast, when conditions are favorable for storage molds, grains are not evenly affected by mycotoxins and distribution is more diverse both across and within storage bins (Jacela et al., 2010).

Mycotoxin contamination most often occurs in grains, such as corn, sorghum, wheat, and barley. Corn is the most extensively and highly contaminated grain (Rodrigues and Naehrer, 2012; Hendel et al., 2017). In addition, mycotoxins are often concentrated in co-products from grains such as corn distillers dried grains with solubles (DDGS) (Rodrigues and Naehrer, 2012). The fermentation process to produce DDGS results in removal of most of the starch in corn and, if corn is contaminated, mycotoxins are unaffected by fermentation and are concentrated by as much as three times the concentration of mycotoxins in the corn source (Jacela et al., 2010).

Types of mycotoxins

Swine are particularly susceptible to mycotoxicosis. Mycotoxicosis is the intoxication that results from the consumption of grains or feeds contaminated with mycotoxins. The degree of mycotoxicosis depends on mycotoxin type and concentration present in the feed and the category of swine consuming the diet. **Table 2** presents the effects of mycotoxicosis in each category of swine according to mycotoxin concentration in the feed. In addition, the Food and Drug Administration determines regulatory limits of aflatoxins to commercialize feed ingredients and feeds for swine to 20 ppb for grower pigs, 200 ppb for finisher pigs over 100 lb BW, and 100 ppb for breeders.

Mycotoxicosis affects many body systems with a wide variety of signs, lesions, and impaired performance. Typically, young pigs and sows are more susceptible and the effects of mycotoxicosis are more evident (Osweiler and Ensley, 2012). Moreover, contamination with more than one mycotoxin is frequent and the combination of mycotoxins often have additive effects (Vila-Donat et al., 2018). However, while there is data available on the effects of a single mycotoxin contamination on swine performance, little is known about the effects of multiple mycotoxin contamination.

Aflatoxin

Aflatoxins are produced by molds of *Aspergillus* species before harvest and in storage. Aflatoxin B_1 is the most abundant and toxic aflatoxin and is often produced by *Aspergillus flavus*. Aflatoxins affect liver function and cause immunosuppression (Osweiler and Ensley, 2012). Acute aflatoxicosis is uncommon in swine but causes severe liver lesions and signs are a consequence of liver disfunction, such as hemorrhages, jaundice, and sudden death (Osweiler and Ensley, 2012). Aflatoxin at lower doses is cumulative. Thus, chronic aflatoxicosis is more common in swine, as a result of ingestion of lower amounts of aflatoxin for a prolonged period of time and is expressed as lower feed intake and growth rate (Devreese et al., 2013). Also, the occurrence of secondary diseases can increase as well as response to vaccination can decrease because of immunosuppression (Pierron et al., 2016). Nursery pigs are more susceptible to aflatoxicosis than grower-finisher pigs or sows. However, suckling piglets are also considered susceptible to aflatoxicosis because aflatoxin passes through milk when sows in lactation consume contaminated feed.

Vomitoxin

Vomitoxin is the term for deoxynivalenol (DON), a mycotoxin produced by *Fusarium graminearum* before harvest. Vomitoxin is the most common contaminant of corn, wheat, and DDGS in North America and Europe (Rodrigues and Naehrer, 2012; Hendel et al., 2017) and swine is the most sensitive species. Vomitoxin interferes with protein synthesis, modulation of immunity, and activity of neurotransmitters in the brain (Osweiler and Ensley, 2012). Despite what the name suggests, vomitoxin rarely induces vomiting in swine. Acute toxicity is uncommon, but in that case vomit, diarrhea, severe digestive lesions, and sudden death occur (Young et al., 1983). Chronic vomitoxin toxicity is more common and of practical importance. In most cases, a sharp decrease in feed intake is evident and, consequently, a reduction in growth rate upon first exposure (Frobose et al., 2015). The impact on feed intake is dose-dependent, with an estimation of 4% decrease in feed intake for every additional ppm of vomitoxin above the dietary concentration of 1.5 ppm (Frobose et al., 2015).

Zearalenone

Zearalenone is produced by *Fusarium graminearum* generally before harvest. Zearalenone is similar in structure and mimics the effects of the hormone estrogen (Zinedine et al., 2007). Thus, the primary effects of zearalenone are in the reproductive tract of swine (Osweiler and Ensley, 2012). In gilts, a characteristic of zearalenone is swelling and redness of the vulva. Rectal and vaginal prolapses often occur. In sows, zearalenone induces modification in heat behavior with either prolongation of standing heat or no manifestation of standing heat. In bred sows, false pregnancy and early embryo loss also occur. During lactation, zearalenone passes through milk and induces vulvar swelling and redness in newborn suckling gilts (Hennig-Pauka et al., 2018). In boars, zearalenone suppresses testosterone levels, sperm production, and libido, particularly in young boars (Benzoni et al., 2008). The normal reproductive performance of swine typically resumes after the removal of zearalenone contamination from the diet.

Fumonisin

Fumonisins are produced by *Fusarium* species before harvest. Fumonisin B_1 is the most abundant fumonisin and is more likely produced by *Fusarium verticillioides*. Fumonisins interfere with cell function and signaling in many tissues, but mainly the lungs, heart, and liver (Haschek et al., 2001). Fumonisins also cause immunosuppression (Pierron et al., 2016). Acute toxicity causes a condition called porcine pulmonary edema, which is characteristic of fumonisin intoxication and causes heart failure and fluid accumulation in the lungs (Haschek et al., 2001; Osweiler and Ensley, 2012). Pigs with acute toxicity have severe respiratory signs, with labored and openmouthed breathing, cyanosis, and death. Chronic toxicity develops as a result of ingestion of smaller amounts of fumonisins for a prolonged period of time. Pigs with chronic toxicity have lower feed intake and lower growth rate, but may also have greater susceptibility to secondary diseases and lower response to vaccination because of suppression of the immune system (Pierron et al., 2016). Fumonisins toxicity to the liver is common and is both time- and dose-dependent (Haschek et al., 2001).

Ochratoxin

Ochratoxin is mainly produced by *Aspergillus ochraceus*, *Penicillium verrucosum*, and *Penicillium viridicatum* during storage. Ochratoxin A is toxic for kidneys and liver (Osweiler and Ensley, 2012). In most of the cases of ochratoxin A toxicity, pigs have low growth rate and poor feed efficiency due to impaired kidney and liver functions. But feed intake is often unaffected (Malagutti et al., 2005). In some cases, the only effect of ochratoxin A toxicity is found at slaughter by the appearance of pale, firm, enlarged kidneys (Stoev et al., 2002). Ochratoxin A contamination is also a concern for human health because pork and pork-derived products may contain ochratoxin residues with carcinogenic potential (Malagutti et al., 2005).

Mycotoxin analysis

Sampling grain or feed for mycotoxins analysis is critical for mycotoxin detection. Mycotoxins are not evenly distributed in grains or feeds. Rather, mycotoxins are often found at high concentrations in 'hot spots', but at the same time may not be found at detectable amounts in other locations. Thus, the ideal sample should be representative of all of the grain or feed. Importantly, the presence or absence of visible mold growth is not a reliable indicator of mycotoxin contamination and should not be used as a sampling criterion (Carlson and Ensley, 2003b).

For bulk grains or feeds, samples should be collected from at least 10 evenly-spaced locations in the bulk carrier to be representative of the entire load of grains or feeds. For sampling during loading or unloading of bulk grains or feeds, samples should be collected at least 10 times at regular intervals. For sampling from bags of grains or feeds, at least 10 bags should be collected from the lot, with random selection of bags at varying locations in the lot. For sampling from feeders, at least 6 feeders should be collected with a probe or 9 feeders by hand grabbing. In either sampling procedure, sample size should be at least 1 lb and preferentially 2 lb (AAFCO, 2017). Samples should be combined in a composite sample.

Samples should be sent for analysis in paper bags rather than plastic bags to prevent condensation of moisture and further proliferation of mold growth (AAFCO, 2017).

Suggested laboratories performing mycotoxin analyses of complete feeds and feed ingredients are North Dakota State University Veterinary Diagnostic Laboratory (www.vdl.ndsu.edu) and Romer Labs, Inc. (www.romerlabs.com).

Management of mycotoxins in swine diets

In the occasion of mycotoxin contamination of grains or feeds, some strategies for mitigation of mycotoxins in swine diets are available (Dänicke, 2002). Importantly, strategic feeding should be adopted in any instance of mycotoxin contamination by preferentially feeding finishing pigs instead of nursery pigs and sows, which are typically more susceptible to mycotoxins.

At low mycotoxin concentration, grains are often used as is in swine diets as long as mycotoxin concentration in the diet is below the levels affecting health and performance (**Table 2**). At high mycotoxin concentration, different strategies can be adopted. Grains can be fed to species less sensitive to mycotoxins, such as cattle, or grains can be blended with clean grains to reduce mycotoxin concentration by dilution (Carlson and Ensley, 2003a). However, both strategies require using clean grains, which may be a challenge when mycotoxin occurrence is widespread. Furthermore, the Food and Drug Administration does not permit aflatoxin-contaminated grains to be blended for commercialization. Alternatively, grains can be screened and cleaned to remove broken kernels and reduce mycotoxin contamination in grains (Yoder et al., 2017). Misshapen and broken kernel are associated with higher mycotoxin concentrations.

The inclusion of mold inhibitors and mycotoxin binders in the feed can be used as a detoxification strategy. Mold inhibitors are used to control mold contamination and prevent mold growth, whereas mycotoxin binders or adsorbents are substances that bind to mycotoxins and prevent absorption through the gut. Mycotoxin binders are not effective against all mycotoxins and must be rather targeted to a specific mycotoxin.

Table 1. Sources and conditions for mycotoxin formation					
Mycotoxin	Mold source	Grains affected	Optimal temperature	Optimal humidity	Favorable conditions
Aflatoxins (B_1, B_2, G_1, G_2)	*Aspergillus flavus, Aspergillus parasiticus*	Corn, sorghum, cotton seed, peanuts	75 to 95°F	80 to 85% relative humidity 17% moisture content	Grain damage, constant high temperature and humidity
Vomitoxin (deoxynivalenol, DON)	*Fusarium graminearum*	Corn, wheat, barley, sorghum, rye, others	79 to 82°F	88% relative humidity 22% moisture content	Alternating warm and cool temperatures during growing season, high humidity
Zearalenone	*Fusarium graminearum*	Corn, wheat, barley, sorghum	45 to 70°F	24% moisture content	Alternating warm and cool temperatures during growing season
Fumonisins (B_1, B_2, B_3)	*Fusarium verticillioides*	Corn	Likely < 77°F	Likely > 20% moisture content	Drought during growing season followed by cool, wet conditions
Ochratoxin A	*Aspergillus ochraceus, Penicillium verrucosum, Penicillium viridicatum*	Corn, wheat, barley, rye	54 to 77°F	85% relative humidity 19 to 22% moisture content	Low temperatures

Adapted from Osweiler and Ensley (2012).

Table 2. Effects of mycotoxicosis according to category of swine and mycotoxin level in the diet

Mycotoxin	Category of swine	Dietary level	Effects
Aflatoxins	Grower-finisher	< 100 ppb	No signs
(B_1, B_2, G_1, G_2)[1]		200 to 800 ppb	Low feed intake, low growth rate, immunosuppression
		800 to > 2000 ppb	Severe liver disfunction, hemorrhages, jaundice, and sudden death
	Breeders	400 to 800 ppb	No signs on breeders, slow-growing suckling pigs due to aflatoxin in milk
Vomitoxin	Grower-finisher	< 1 ppm	No signs
(deoxynivalenol, DON)		2 to 8 ppm	Sharp decrease in feed intake, low growth rate
		10 ppm	Complete feed refusal, vomit, diarrhea, severe digestive lesions, sudden death
Zearalenone	Gilts and sows	1 to 3 ppm	Vulvar swelling and redness, prolapses of rectum and vagina
		3 to 10 ppm	Anestrus, false pregnancy
		> 30 ppm	Early embryo loss
	Boars	> 40 ppm	Low libido
Fumonisins (B_1, B_2, B_3)	All swine	< 20 ppm	No signs
		50 to 100 ppm	Low feed intake, low growth rate, immunosuppression
		> 100 ppm	Severe lung lesions, labored breathing, cyanosis, and death
Ochratoxin A	Grower-finisher	200 ppb	Low growth rate, poor feed efficiency, kidney lesions at slaughter
		> 1000 ppm	Severe kidney disfunction

Adapted from Osweiler and Ensley (2012).

[1]Food and Drug Administration regulatory limits of aflatoxins to commercialize feed ingredients and feeds for swine: 20 ppb for grower pigs, 200 ppb for finisher pigs over 100 lb BW, and 100 ppb for breeders.

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Economics in Swine Nutrition

The nutritional program for swine has a major influence on profitability as feed cost accounts for up to 75% of swine production cost. The economics involving a nutritional program for swine include feed cost, feed cost per unit of gain, and income over feed cost. Some economic concepts and examples of use of economics in swine nutrition are discussed in this fact sheet.

Economics of a nutritional program

Determining the economic value of a nutritional program is a different process for each production system. There are three potential methods for determining the economics of a nutritional program: feed cost, feed cost per unit of gain, and income over feed cost.

Feed cost

Feed cost only takes into consideration the cost of the diets for comparison between one nutritional program versus another. This method is the simplest and has its greatest and best application when there is no expected change in pig performance associated with nutritional program. However, because changes in ingredients or nutrient levels often change pig performance, it should rarely be used as the main evaluation of economic competitiveness of a feeding program.

Feed cost per unit of gain

Feed cost per pound of gain is calculated by multiplying feed efficiency by the feed cost per pound. The best application of this method is for comparison between nutritional programs when there is an expected change in feed efficiency without a change in growth rate.

Feed cost per pound of gain, $/lb gain =

Feed efficiency × Feed cost, $/lb

Income over feed cost

Income over feed cost (IOFC) is a margin of profit calculated by subtracting feed cost from the revenue, usually on a per pig basis. Revenue per pig is often estimated by multiplying hot carcass weight by hot carcass weight price, or by multiplying total weight gain by live weight price. Feed cost per pig is estimated by multiplying total feed intake by feed cost. Facility cost can be also added to feed cost to estimate the income over feed and facility cost (IOFFC). Typically, facility cost in the United States is around $0.10 to 0.12 per pig per day.

IOFC and IOFFC are accurate methods to determine the economic value of a nutritional program. The best application is for systems that run on a fixed-time basis and for comparison between nutritional programs when there is an expected or possible change in both feed efficiency and growth rate.

Income over feed cost, $/pig =

Revenue, $/pig - Feed cost, $/pig

Income over feed and facility cost, $/pig =

Revenue, $/pig – (Feed cost + Facility cost, $/pig)

Examples of use of economics

The use of economics in swine nutrition is exemplified by the economics of using fats or oils and by the economics of using distillers dried grains with solubles.

Economics of using fats or oils

Energy is the most expensive component of the diet. The use of fat in the diet increases dietary energy and has direct impact on growth rate, feed efficiency, and carcass criteria. The use of fat should be based on an economic analysis to determine the most economical dietary energy level considering the value of incremental changes in energy on production indicators and the market price.

A production tool has been developed to aid in determining the optimum dietary energy level in the grow-finish phase (Net Energy Model). Also, using the appropriate method to evaluate the economics of using fat is essential to determine the most cost-effective diet.

The example in **Table 1** illustrates the use of feed cost, feed cost per pound of gain and income over feed cost, to determine the economics of added dietary fat. The example is a comparison between two nutritional programs with or without 5% added fat in grow-finish diets. The assumption is that diets with added fat are approximately 20% more expensive but result in 10% improvement in feed efficiency and 5% increase in average daily gain in a system running on a fixed-time basis.

In this example, considering feed cost or feed cost per pound of gain, the nutritional program without added fat to grow-finish diets would be more economical. However, taking into account the extra weight gain and improvement in feed efficiency with added fat, there is a $0.76 per pig advantage in income over feed cost with a nutritional program with added fat to grow-finish diets. This would be the interpretation in a system that runs on a fixed-time basis. However, if the system runs on a fixed-weight basis and could take longer to achieve a heavier carcass weight, then feed cost per pig would also be an adequate indicator of the economic value of the nutritional program.

Table 1. An example on how to determine the economic value of added dietary fat in grow-finish diets

Assumptions:	
Diets without added fat	Diets with 5% added fat
- Feed cost: $160/ton or $0.08/lb	- Feed cost: $190/ton or $0.095/lb
- Initial BW: 50 lb	- Initial BW: 50 lb
- F/G: 2.8	- F/G: 2.5
- ADG: 1.80 lb	- ADG: 1.90 lb
- 130 days in the grow-finisher	- 130 days in the grow-finisher
- Final BW: 50 lb + (1.80 lb × 130 d) = 284 lb	- Final BW: 50 lb + (1.90 lb × 130 d) = 297 lb
- Yield: 75%	- Yield: 75%
- HCW: 284 lb × 0.75 = 213 lb	- HCW: 297 lb × 0.75 = 223 lb
- HCW price: $0.70/lb	- HCW price: $0.70/lb
Calculations:	
Feed cost = $160/ton or $0.08/lb	Feed cost = $190/ton or $0.095/lb
Feed cost per lb of gain = 2.8 × $0.08 = $0.224/lb gain	Feed cost per lb of gain = 2.5 × $0.095 = $0.237/lb gain
Income over feed cost = revenue – feed cost	Income over feed cost = revenue – feed cost
Revenue = HCW × HCW price = 213 lb × $0.70 = $149.10	Revenue = HCW × HCW price = 223 lb × $0.70 = $156.10
Feed cost = F/G × ADG × days in finisher × feed cost, $/lb	Feed cost = F/G × ADG × days in finisher × feed cost, $/lb
= 2.8 × 1.80 lb × 130 d × $0.08 = $52.42	= 2.5 × 1.90 lb × 130 d × $0.095 = $58.66
Income over feed cost = $149.10 – $52.42 = $96.68/pig	Income over feed cost = $156.10 – $58.66= $97.44/pig

Economics of using distillers dried grains with solubles

Corn distillers dried grains with soluble (DDGS) is an economical and widely available feed ingredient for use in swine diets. The economic value of DDGS depends on cost of corn and soybean meal, as DDGS replaces both ingredients in the diet. The favorable price of DDGS relative to corn and soybean meal is often an incentive to greater DDGS inclusion rates. However, dietary inclusion rates of DDGS in grow-finish diets have an impact on growth performance, carcass yield, and pork fat firmness, which affect the economic return of the nutritional program.

A production tool has been developed to aid in determining the economic DDGS levels for grow-finish diets. The KSU DDGS Calculator estimates the economic return from using dietary DDGS at varying levels by considering changes in feed cost and growth performance. However, the impact of DDGS levels on carcass yield or pork fat firmness is not accounted for.

The example in **Figure 1** illustrates the use of the KSU DDGS Calculator. The calculator suggests the DDGS inclusion rate in grow-finish diets to maximize savings per pig. Then, the user can choose the most appropriate DDGS level for the production system. In this example, using a maximum of 30% DDGS in a step-down program would result in savings of $2.67 per pig.

K-State DDGS Calculator (Variable DDGS Energy)

Calculator attempts to consider economic return per pig from change in diet cost, feed efficiency, and growth rate. It does not account for any economic impact on yield or iodine value.

Corn, $/bu	$ 3.25	$ 116.07	**112%** =DDGS to Corn price ratio
SBM, $/ton	$ 290.00		
Monocal, $/ton	$ 460.00		
Limestone, $/ton	$ 50.00		
Lysine HCl, $/lb	$ 0.70		
DL-Met, $/lb	$ 1.20		
L-Threonine, $/lb	$ 0.90		
DDGS, $/ton	$ 130.00		

Use fat to equalize energy	Yes
Include L-Trp in diets?	Yes
Energy as % of corn or oil content	Oil, %
DDGS oil content, %	8.0%
Value of pig gain, $/lb	$ 0.70
Fat, $/lb	$ 0.20
L-Trp, $/lb	$ 3.90

DDGS NE, % of corn
90.6%

Start weight, lb	**50**	**75**	**125**	**170**	**210**	**246**	
End weight, lb	**75**	**125**	**170**	**210**	**246**	**280**	
DDGS maximum value	**F1**	**F2**	**F3**	**F4**	**F5**	**F6**	**Total**
DDGS % at max savings	**40**	**40**	**40**	**30**	**25**	**20**	
Max savings, $/pig	**$0.46**	**$1.01**	**$0.93**	**$0.77**	**$0.62**	**$0.49**	**$4.26**
DDGS levels chosen	**30%**	**30%**	**30%**	**20%**	**10%**	**0%**	
- Savings, $/pig	**$0.35**	**$0.77**	**$0.76**	**$0.52**	**$0.27**	**$0.00**	**$2.67**

Figure 1. An example on how to determine the economic DDGS level in grow-finish diets using the KSU DDGS Calculator.

Key Concepts for a Successful Nursery Nutrition Program

Understanding the main concepts of nursery is key to designing a nutrition program for weaned pigs. The key concepts for a successful nursery nutrition program are discussed in this fact sheet.

Wean good quality pigs

A key recommendation to improve quality of pigs at weaning is to wean pigs as old and as heavy as feasible. Weaning age averages 19 to 23 days in most swine production systems in the United States. Age at weaning greatly influences weaning weight and post-weaning growth rate. After weaning, pigs undergo a period of adaptation, which contributes to lower feed intake and growth performance, impairment of gut barrier function, and greater susceptibility to diseases. Weaning pigs with at least 21 days of age is beneficial to ameliorate the stressful effects of weaning and improve growth performance in the nursery and finisher (Main et al., 2004; Moeser et al., 2007).

Improvements in growth performance and mortality from wean to finish are evident when weaning age is increased through at least 21 days of age (Main et al., 2004). The ability of late weaned pigs to perform better is not only a consequence of heavier weight at weaning, but most importantly a consequence of a physiological change in the pig. Indeed, late weaned pigs have improved gut barrier function (Moser et al., 2007; Smith et al., 2010) and immune response against pathogens (McLamb et al., 2013) compared to early weaned pigs.

Maximize feed intake after weaning

Feed intake is a key determinant of performance and health status of weanling pigs. While the majority of pigs begin consuming feed within the first 24 hours after weaning, approximately 30% take between 24 and 60 hours to start on feed (Bruinix et al., 2001). Weanling pigs are in a highly energy-dependent stage of growth, which means that any increase in feed intake results in improvements in growth rate and lean deposition. Moreover, feed intake is important to sustain an adequate gut structure for nutrient absorption (Pluske et al., 1996) and to reduce the occurrence of diarrhea in weanling pigs (Madec et al., 1998).

The most important aspect to maximize feed intake is to have feed available and offered *ad libitum* as soon as pigs are weaned. There are several strategies to encourage feed intake of weanling pigs. One strategy is to use feeding boards or mats to supply adequate feeding space. Another strategy is to offer a gruel with a mixture of feed with water. With both of these strategies, feed should also be available in the feeders and the strategies should be used temporarily during the first few days after weaning as to not discourage consumption of feed in the feeders. The boards, mats, and gruels should be appropriately managed to prevent feed spoilage and disease transmission.

Feeding behavior after weaning is also stimulated by providing creep feed while pigs are nursing to ease the transition from milk to solid diets (Bruinix et al., 2002). The creep diet doesn't have to be offered for a long duration before weaning (Sulabo et al., 2010), but it must be a highly palatable and digestible diet (Sulabo et al., 2009). A viable strategy is to offer a creep diet for 3 d before weaning to increase the proportion of pigs consuming creep feed and improve feed intake after weaning. Also, using similar ingredients in initial nursery diets can stimulate weanling feed intake in the early post-weaning.

Provide proper management

Management is key for a successful nutritional program in the nursery. Proper management involves maintaining a comfortable environmental temperature for weanling pigs, adequate ventilation, early identification and treatment of sick pigs, and proper feeder and waterer adjustment.

Feeder adjustment is important to encourage feed intake and improve feed efficiency in the nursery. In general, it is recommended to adjust feeders to allow for approximately 50% of feeder pan coverage. The amount of feed flowing into the pan should be greater in the early post-weaning period to stimulate feeding behavior and then gradually adjusted to control feed wastage. However, the influence of feeder adjustment on feed wastage seems to be variable depending on feeder design.

With high quality feeders, a wide feeder gap opening and a feeder pan coverage between 50 to 75% can be used while still achieving good feed efficiency (Smith et al., 2004; Nemechek et al., 2015).

Waterer adjustment is essential to facilitate water access as well as to ensure water cleanliness and a continuous supply of fresh water. In general, it is recommended to adjust waterer height as nursery pigs grow. Cups and nipples mounted at a 90° angle should be adjusted at shoulder height, whereas nipples mounted at a 45° angle should be set at 2 to 3 inches over shoulder height.

Remember the biology of the pig

The biology of weanling pigs must be considered for a successful nutritional program in the nursery. Young pigs have high protein deposition, low feed intake, high lactase activity, and low amylase, maltase, sucrase, and lipase activities. This means that newly weaned pigs are able to easily digest lactose and specialty protein sources, but have limited ability to digest plant protein sources, sugars, and to utilize fat. In general, it is important to provide adequate amino acid levels from highly digestible protein sources because weanling pigs have a high capacity for protein deposition in relation to feed intake level. However, it is not effective to use fat to increase the energy density of the diet to counteract the low feed intake level.

Adjust pigs to simple diets as quickly as possible

One of the goals of the nutritional program in the nursery is to prepare pigs for grow-finish diets. Diets in the grow-finish are relatively simple and less expensive compared to nursery diets. Although the use of specialty ingredients results in excellent performance in the nursery, benefits do not result in further improvement in grow-finish performance. Thus, specialty ingredients should be paid for in the nursery without projections of improved finishing performance. The goal is to gradually remove specialty high-cost ingredients from nursery diets and replace them with typical lower-cost ingredients, such as grains and soybean meal, as quickly as possible.

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Specialty Ingredients in Nursery Diets

Highly-digestible, nutrient-dense, specialty feed ingredients in nursery diets are often used to improve feed intake and performance of newly weaned nursery pigs. The most common feed ingredients with specific application in nursery diets are discussed in this fact sheet.

Protein sources

Dietary protein sources can be derived from plant or animal sources. Plant protein sources are typically less expensive than animal protein sources, but may contain various anti-nutritional factors. Animal protein sources are typically palatable and contain highly digestible amino acids, but variability in composition is often greater than plant sources. The interest in the use of plant-based protein sources is growing because of biosecurity concerns related to feeding animal-based protein sources.

Plant protein sources

Plant protein sources provide most of the protein in swine diets and soybean meal is the leading protein source. However, soybean meal might not be suitable to be fed as sole protein in the early post-weaning period.

Pigs have a transitory hypersensitivity reaction to soybean meal induced by allergenic proteins, namely glycinin and β-conglycinin, and indigestible carbohydrates of soybeans. Pigs experience a transitory period of poor nutrient absorption and low growth performance following the first exposure to a diet with high amounts of soybean meal (Li et al., 1990). The effects are transitory and pigs develop tolerance after 7 to 10 days (Engle, 1994). To alleviate the effects during this period, pigs are gradually acclimated to diets with increasing amounts of soybean meal after weaning.

The initial post-weaning diets should contain low amounts of soybean meal and then gradually increase soybean meal in the following nursery diets. The early exposure to soybean meal reduces the potential for delayed-type hypersensitivity reaction and adjusts the pig to diets containing soybean meal as the primary protein source. Furthermore, soybean meal can be further processed to remove the allergenic compounds and improve the utilization of soy proteins by weanling pigs (Jones et al., 2010).

♦ Fermented or enzyme-treated soybean meal

Further-processed soybean meal by microbial fermentation or enzymatic treatment is done to reduce the allergenic proteins and indigestible carbohydrates of soybeans (Stein et al., 2016). Microbial fermentation is usually accomplished by the inclusion of microbes to soybean meal, such as *Aspergillus oryzae*, *Bifidobacterium lactis*, *Lactobacillus subtilis*, among others. Enzymatic treatment is commonly performed by inclusion of proprietary enzymes and yeast to soybean meal (Stein et al., 2016).

Fermented or enzyme-treated soybean meal have greater concentration of crude protein than soybean meal, approximately 50 to 55% (Cervantes-Pahm and Stein, 2010; Jones et al., 2010). However, the standardized ileal digestibility of most amino acids and particularly lysine is lower in fermented or enzyme-treated soybean meal compared to conventional soybean meal (Cervantes-Pahm and Stein, 2010). The reduction in digestibility of amino acids is due to heat during the drying process to produce fermented or enzyme-treated soybean meal.

The inclusion of fermented or enzyme-treated soybean meal by up to approximately 10% in nursery diets in place of other high-quality protein sources does not adversely affect nursery performance (Jones et al., 2010; Kim et al., 2010; Yuan et al., 2017). However, greater inclusion rate of the enzyme-treated soybean meal can reduce feed intake of nursery pigs (Jones et al., 2018b). In general, specialty soy protein products provide an opportunity to reduce soybean meal content in diets for weanling pigs.

♦ Soy protein concentrate and isolate

Soy protein concentrate and isolate are high protein products derived from dehulled, de-oiled soybeans (or soy flakes). Soy protein concentrate contains at least 65% crude protein and soy protein isolate is the most concentrated soy protein source, with at least 85% crude protein (NRC, 2012).

During processing of soy protein concentrate and isolate, the allergenic proteins and indigestible carbohydrates of soybeans are mostly removed (Stein et al., 2016). However, the antinutritional factor trypsin inhibitor might be present in greater quantities compared to soybean meal because processing does not necessarily involve heat-treatment (Cervantes-Pahm and Stein, 2010).

The inclusion of soy protein concentrate at approximately 14% in nursery diets improves growth performance compare to soybean meal. However, greater inclusion rates may affect palatability and reduce feed intake (Lenehan et al., 2007). The cost of soy protein isolate is usually prohibitive to use in nursery diets.

Animal protein sources

Animal protein sources have been commonly used to minimize soybean meal inclusion in initial nursery diets and encourage feed intake in weanling pigs. Animal protein sources are typically palatable and contain highly digestible amino acids. However, animal protein sources are more expensive and variability in composition is often greater than plant protein sources.

Biosecurity concerns arise from the potential disease transmission via animal-sourced ingredients, particularly porcine-based. Animal protein sources typically undergo a thermal processing that eliminates most pathogens, but post-processing recontamination can be a concern. In addition, some pork marketing programs may limit the use of animal protein sources in swine diets.

♦ Spray-dried blood products

Spray-dried blood products are by-products obtained from swine and bovine slaughter plants. Spray-dried blood cells and spray-dried plasma are produced by separating the blood fractions, whereas spray-dried blood meal contains both blood cells and plasma (Almeida et al., 2013).

Spray-dried blood products are often used in diets for weanling to enhance feed intake and growth rate in the early post-weaning. Spray-dried blood products are able to stimulate feed intake either as spray-dried plasma or as spray-dried blood meal (DeRouchey et al., 2002). Most of the benefits of spray-dried plasma are in the early post-weaning period, with typical inclusion rates up to 6% spray-dried plasma in initial nursery diets (van Dijk et al., 2001; Remus et al., 2013). Spray-dried porcine plasma may provide slightly more benefit than spray-dried bovine plasma (van Dijk et al., 2001), but concerns with biosecurity are greater (Aubry et al., 2017).

Spray-dried blood products contain high concentration of crude protein (75 to 90%) and lysine (7 to 8%) (NRC, 2012). Standardized ileal digestibility of lysine and most amino acids is high, above 95 to 95% (Almeida et al., 2013). However, lysine availability is reduced with use of excessive heating during processing of spray-dried blood products.

The use of spray-dried blood products requires attention to a favorable balance of branched-chain amino acids due to the high concentration of leucine but low concentration of isoleucine and valine, particularly in spray-dried blood cells or blood meal (Kerr et al., 2004; Goodband et al., 2014). Also, the concentration of methionine is low in all spray-dried blood products. The inclusion of other protein sources or supplementation of diets with feed-grade amino acids is important to adjust the amino acid profile in diets with spray-dried blood products (Remus et al., 2013).

Spray-dried blood products may vary substantially in composition and quality according to source and processing methods. The application of heat is critical to eliminate pathogens (Narayanappa et al., 2015), but post-processing recontamination can be a concern. In order to minimize the risk of disease transmission via feed ingredients, it is advisable to only use non-porcine-derived blood products.

♦ Meat and bone meal

Meat and bone meal is a by-product from various tissues obtained from harvesting plants. Meat and bone meal contains high concentrations of crude protein (50 to 55%), lysine (2.5%), and most amino acids except for tryptophan (NRC, 2012). Standardized ileal digestibility of lysine and most amino acids is low, approximately 65 to 80% (Kong et al., 2014). Moreover, lysine availability is further reduced with use of excessive heating during processing of meat and blood meal.

Meat and bone meal is an excellent source of calcium and phosphorus, providing the minerals in high concentration and with a high phosphorus bioavailability (Traylor et al., 2005).

Meat and bone meal quality and composition may vary substantially according to the raw materials characteristics. The thermal processing of meat and bone meal is critical to eliminate pathogens, but post-processing recontamination can be a concern. In order to minimize the risk of disease transmission via feed ingredients, it is advisable to only use non-porcine-derived meat and bone meal.

♦ Poultry meal

Poultry meal is a by-product from viscera and various tissues obtained from poultry harvest. Poultry meal contains high concentration of crude protein (60 to 65%), lysine (4%), and most amino acids except for tryptophan (NRC, 2012). The digestibility of amino acids can be affected by the ash content of poultry meal. The ash content is directly related to the level of bone included in poultry meal and is a measure associated with low digestibility and inferior quality (Keegan et al., 2004). Moreover, lysine availability is further reduced with use of excessive heating during processing of poultry meal.

Poultry meal quality and composition may vary substantially according to the raw materials characteristics. The thermal processing of poultry meal is critical to eliminate pathogens, but post-processing recontamination can be a concern

♦ Fish meal

Fish meal is a product obtained by processing whole fish or fish waste. Fish meal typically contains high concentration of crude protein (60 to 65%) and lysine (4.5%), favorable amino acid profile, and omega-3 fatty acids (NRC, 2012). Standardized ileal digestibility of lysine and most amino acids is high, approximately 85% (Cervantes-Pahm and Stein, 2010).

The inclusion of fish meal in nursery diets enhances palatability and usually increases feed intake with a typical inclusion of approximately 3 to 6% fish meal (Jones et al., 2018a).

Fish meal quality can vary considerably depending on the species of fish, raw fish freshness, and processing method (Kim and Easter, 2001; Jones et al., 2018a). Fish solubles, also known as stickwater concentrate, is a by-product rich in B vitamins and minerals derived from fish meal processing. The amount of fish solubles is variable in fish meal, generally found at 8 to 15%, but it is not associated with fish meal quality or nursery pig performance (Jones et al., 2018a).

Currently, there is no single laboratory test that provides a general estimate of fish meal quality. Analysis of mineral content and fat can be used as an indicative of fish meal feeding value. Fish meal with high mineral content (> 20%) and lower fat level (< 7.5%) is generally from fish offal and contains lower feeding value compared to fish meal from whole fish. Freshness of raw fish can be estimated by analysis of total volatile nitrogen. Values below 0.15% total volatile nitrogen generally indicate fish meal freshness. Bacterial analysis is important to assess quality of fish meal, as *Salmonella* can be transmitted via fish meal (Morris et al., 1970).

♦ Porcine intestinal mucosa products

Porcine intestinal mucosa products are by-products of the pharmaceutical industry obtained from processing of porcine intestinal mucosa to extract the anticoagulant heparin. Commercially available products are generally referred to as enzymatically-hydrolyzed intestinal mucosa, dried porcine solubles, or peptones. The concentration of crude protein is high (50 to 60%) and amino acid profile is favorable (Myers et al., 2014). Standardized ileal digestibility of lysine and most amino acids is high, above 80 to 85% (Sulabo et al., 2013).

Porcine intestinal mucosa products provide small peptides that are easily digestible by nursery pigs. Porcine intestinal mucosa products can be added at approximately 6% in nursery diets (Myers et al., 2014).

Variation in composition of porcine intestinal mucosa products is due to different plant proteins used as carriers during drying and processing of intestinal mucosa (Jones et al., 2010; Myers et al., 2014). The thermal processing of porcine intestinal mucosa products is critical to eliminate pathogens, but post-processing recontamination can be a concern.

♦ Spray-dried egg

Spray-dried egg is a by-product from the egg industry produced only from eggs without shell that do not meet the quality standards for human consumption. Spray-dried egg contains high concentration of crude protein (50%), lysine (3.5%), and favorable amino acid profile (NRC, 2012).

Spray-dried egg provides bioactive compounds, such as antimicrobial proteins (lysozyme) and antibodies (IgY). The composition of spray-dried egg is thought to provide benefits to improve health (Song et al., 2012). Moreover, hens can be immunized against pathogens, such as enterotoxigenic *Escherichia coli*, and the hyperimmunized eggs serve as a pathogen-specific antibody source (Da Rosa et al., 2014).

♦ **Whey protein concentrate**

Whey protein concentrate is produced by having an additional process of ultrafiltration of liquid whey before the drying process (Grinstead et al., 2000). The ultrafiltration process concentrates the whey protein and removes most of the lactose. Whey protein concentrate contains 75 to 80% crude protein and low lactose concentration, generally around 5% (NRC, 2012). Whey protein concentrate is an edible-grade product in high demand by the food industry, limiting its availability for use in nursery diets.

Yeast protein source

♦ **Dried fermentation biomass**

Dried fermentation biomass consists of residual material from the feed-grade amino acid production. Feed-grade amino acids are derived from amino acid-producing bacteria in a process that requires a carbon source (sugars) and a nitrogen source (yeast extract) for bacterial fermentation. The fermentation biomass left after extraction of crystalline amino acids is used to produce dried fermentation biomass.

Dried fermentation biomass contains high concentration of crude protein (around 80%), lysine, and essential amino acids (Sulabo et al., 2013; Almeida et al., 2014). Standardized ileal digestibility of lysine and most amino acids is high, above 90% (Sulabo et al., 2013; Almeida et al., 2014).

Dried fermentation biomass can be added at approximately 15 to 20% in nursery diets (Sulabo et al., 2013; Almeida et al., 2014). However, high levels can have a negative impact on feed intake, which could be related to the amount of amino acid-producing bacteria within the dried fermentation biomass. The amino acid-producing bacteria are not harmful to pigs, but a structural component of Gram-negative bacteria (lipopolysaccharide) may have endotoxin activity (Wallace et al., 2016), which affects feed intake.

Feed-grade amino acids

Feed-grade amino acids have been used to reduce specialty protein sources in nursery diets. The replacement of intact protein sources by feed-grade amino acids increases as feed-grade amino acids become available and economically justifiable. Currently, feed-grade lysine, methionine, threonine, tryptophan, and valine are all economical to include in nursery diets in the United States.

The use of feed-grade amino acids is key to meeting the amino acid requirements of nursery pigs, with accompanying reduction in dietary crude protein and savings in diet cost. However, it is important to ensure a sufficient supply of nitrogen for synthesis of non-essential amino acids when formulating diets with high levels of feed-grade amino acids.

Carbohydrate sources

Starch carbohydrates are an excellent energy source for pigs. However, in the early period after weaning, carbohydrate sources must be highly digestible to serve as a readily available source of energy for weanling pigs, particularly to counteract the low feed intake after weaning.

Lactose

Lactose is the carbohydrate component derived from milk and provides an easily digestible source of energy for pigs. The addition of lactose in nursery diets improves growth rate of weanling pigs, particularly in the early period after weaning (Tokach et al., 1995; Grinstead et al., 2000). There is a benefit of providing 5 to 30% dietary lactose during the entire nursery period (Mahan et al., 2004; Cromwell et al., 2008), but it is recommended to direct the use of lactose to initial nursery diets and for a short period of time because the magnitude of response dramatically decreases, and lactose products are expensive. Typically, initial nursery diets contain around 18% lactose (Mahan et al., 2004).

Common lactose sources are crystalline lactose (100% lactose), whey permeate (80% lactose), and dried whey (72% lactose). Whey products also provide a source of protein to the diet. When replacing one lactose source by another in the diet, care must be taken to evaluate both lactose and amino acids levels. The key is to know the lactose concentration and replace on an equal lactose basis, and then replace the amino acids with an appropriate high-quality protein source.

Whey products are derived from milk curdling during production of milk products like cheese and yoghurt (Grinstead et al., 2000). Whey products used in nursery diets are preferentially derived from cheese production ('sweet whey') rather than yoghurt production ('acid whey'). The use of edible-grade whey are also preferred over feed-grade whey products (Nessmith et al., 1997).

Quality of whey products is affected by excessive heat during processing, which reduces lactose and amino acid contents and results in whey with a brownish color.

Over-heating also reduces digestibility of lactose and amino acids, which leads to scouring in pigs. Spray-drying is the preferred method to prevent over-heating because of the fast evaporation at lower temperatures compared to roller drying (Grinstead et al., 2000). The levels of minerals also vary during processing and above 11% mineral content leads to scouring in pigs (Nessmith et al., 1997). Indicators of high-quality whey products include white or yellowish color, absence of black specs, and mineral content below 8.5% (Nessmith et al., 1997).

From a feed milling standpoint, the addition of lactose products in the diet influences feed processing. For pelleted diets, high levels of lactose can increase friction during the pelleting process. In this case, the addition of fat in nursery diets with high levels of lactose is often used to enhance lubrication of the pellet die and prevent heat damage. For meal diets, high levels of lactose can increase bridging and reduce flowability in bins and feeders.

Sucrose

Sucrose is a simple carbohydrate extracted from sugar cane or sugar beet. Sucrose provides an easily digestible source of energy for pigs from glucose and fructose. Young pigs have limited ability to utilize sucrose, but sucrase activity rapidly increases after weaning.

Sucrose can be considered as a replacement for lactose in nursery diets, particularly in diets with no animal-based products. The addition of 5 to 10% sucrose in initial nursery diets improves growth performance of weanling pigs as effectively as lactose (Mavromichalis et al., 2001). Products based on sucrose and other simple sugars can also partially replace lactose without an impact on growth performance (Naranjo et al., 2010; Guo et al., 2015).

Dextrose

Dextrose is a form of glucose typically extracted from corn that provides an easily digestible source of energy for pigs. Similar to sucrose, the use of dextrose or products based on dextrose and other simple sugars can partially replace lactose in initial nursery diets without an impact on growth performance (Turlington et al., 1989; Mahan and Newton, 1993; Bergstrom et al., 2007).

Fat sources

Weanling pigs have limited ability to digest and utilize fat to improve growth performance (Tokach et al., 1995). The ability to utilize fat improves with age, particularly for animal fats compared with vegetable oils.

In the early post-weaning period, weanling pigs seem to require a more digestible fat source rich in unsaturated and short-chain fatty acids for efficient energy utilization (Gu and Li, 2003). Vegetable oils like soybean oil and coconut oil are high quality sources of energy for weanling pigs (Weng, 2016), but cost often limits the use in nursery diets. Animal fat sources of good quality like choice white grease or beef tallow are usually more cost-effective to use in nursery diets.

The addition of 3 to 4% fat is mainly used to improve the pelleting process of initial nursery diets with high levels of lactose. As fat utilization for growth performance gradually improves with age, 1 to 3% fat can be added to nursery diets depending on economics.

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Nursery Phase Feeding Program

The purpose of phase feeding is to match the nutrient requirements and digestive capabilities of nursery pigs with the most economical diet possible to achieve optimal performance in the nursery. An example of a nursery phase feeding program is discussed in this fact sheet.

Feed budget

The phase feeding program is often matched to the weight of piglets at weaning using a feed budget. Generally, as pigs become heavier at weaning, the amount of the initial nursery diets is reduced. As an example, a 3-phase feeding program can be used in the nursery, consisting of phase 1 (12 to 15 lb), phase 2 (15 to 25 lb), and phase 3 (25 to 50 lb) diets. An intensive care diet can be used in the nursery for low weaning weight pigs (8 to 12 lb), health-challenged pigs, as well as be offered as a creep feed during the nursing phase.

Intensive care and phase 1 diets are more complex to improve feed intake and provide high-quality feed ingredients to weanling pigs, such as specialty protein and lactose sources. Intensive care and phase 1 diets are commonly provided as pellets or crumbles because of the impact of specialty ingredients on feed flowability. These diets are more expensive, but the use might be justifiable considering the low amount of feed use. Diet complexity rapidly reduces in phase 2 and 3 diets as feed intake is already established. Phase 2 and 3 diets can be provided either as meal, pellets, or crumbles. These diets represent most of the total feed use in the nursery and have a significant impact on total feed cost in the nursery. Adhering to the feed budget guidelines in **Table 1** helps to optimize performance in the nursery and minimize overfeeding of expensive initial nursery diets.

Table 1. Feed budget recommendations for nursery diets according to weaning weight

	Weaning weight, lb						
Diet, lb per pig	10	11	12	13	14	15	16
Intensive care	2	1	1	-	-	-	-
Phase 1	6	5	4	3	2	1	1
Phase 2	12 to 15						
Phase 3	45 to 50						

Diet complexity

Diet complexity refers to the use of highly-digestible specialty feed ingredients in nursery diets. Complex diets are typically fed to weanling pigs to provide high-quality feed ingredients and improve intake in the early post-weaning period. As complex diets are more expensive, diet complexity should be rapidly reduced during the course of the nursery.

Nutritional strategies in the nursery have been of great interest because it is generally assumed that pigs that grow faster in the nursery also grow faster in the finisher. However, not all dietary efforts to improve performance in the nursery are rewarded with improvements in growth rate in the finisher. An important distinction to make is whether the dietary effort is able to induce a fundamental or a transitory change in the nursery pig.

Weaning age is able to induce a fundamental change in the pig. The enhancement of nursery performance by increasing weaning age is typically maintained into the finisher as a consequence of increasing weaning weight (Main et al., 2004), but most importantly as a consequence of a physiological change in the pig, like improvements in digestive and immune functions (Moser et al., 2007; Smith et al., 2010; McLamb et al., 2013).

Most nutritional strategies induce a transitory change in the pig, with improvements in performance while being fed in the nursery, but not necessarily in the subsequent finisher period. Diet complexity typically generates this type of response, with significant improvements in feed intake and growth rate while the complex diet is being fed, but no performance advantages thereafter (Whang et al., 2000; Wolter et al., 2003; Skinner et al., 2014; Collins et al., 2017). This is also the case of amino acid concentration (Main et al., 2008), fat (Tokach et al., 1995), antibiotics (Skinner et al., 2014), or milk replacers (Wolter and Ellis, 2001) in nursery diets. In contrast, lactose is able to improve nursery performance with further improvements in finisher performance (Tokach et al., 1995).

Therefore, the value of diet complexity should consider the benefit gained during the feeding period but not projected additional benefit in the subsequent nursery or finisher periods.

Intensive care diet

The intensive care diet is typically fed to pigs from 8 to 12 lb of body weight. The purpose is to provide nutritional support for piglets that require intensive care, which typically are early-weaned, low-weight, or health-challenged piglets. These pigs represent approximately 10 to 12% of all nursery pigs. The intensive care diet can also be offered as a creep feed during the nursing phase.

The intensive care diet must provide high-quality feed ingredients to stimulate feed intake and match the digestive capabilities of weanling pigs. Typically, the intensive care diet contains high amounts of specialty protein sources such as fermented soybean meal, enzyme-treated soybean meal, soy protein concentrate, spray-dried plasma, or fish meal, among others. The level of lactose is also high, with at least 18% and up to 30% lactose.

Phase 1 diet

The phase 1 diet is typically fed to pigs from weaning at approximately 12 lb until approximately 15 lb of body weight. During this phase, it is important to provide high-quality feed ingredients to stimulate feed intake and match the digestive capabilities of weanling pigs.

Newly weaned pigs are able to easily digest lactose and specialty proteins but have limited ability to digest plant proteins and utilize fat. Pigs also have a hypersensitivity reaction to soybean meal induced by allergenic proteins and indigestible carbohydrates of soybeans. Pigs experience a transitory period of poor nutrient absorption and low growth performance following the first exposure to a diet with high amounts of soybean meal (Li et al., 1990). The effects are transitory and pigs develop tolerance after 7 to 10 days (Engle, 1994). The best approach to alleviate this problem is to expose weanling pigs to increasing levels of soybean meal in nursery diets to allow pigs to gradually overcome the hypersensitivity reaction. The early exposure to soybean meal reduces the potential for delayed-type hypersensitivity reaction and allows for greater inclusion levels in subsequent nursery diets without an impact on growth performance.

Soybean meal is commonly included at up to 16 to 18% in the phase 1 diet. Other specialty protein sources often used in combination are fermented soybean meal, enzyme-treated soybean meal, soy protein concentrate, spray-dried plasma, or fish meal, among others. Typically, the sources are used in combination to achieve the adequate amino acid profile in the diet and because most specialty protein sources cannot be the sole protein source in the diet without affecting palatability or performance.

Lactose is the carbohydrate component derived from milk and provides an easily digestible source of energy for pigs. The phase 1 diet typically contains around 18% lactose to improve growth rate of weanling pigs (Tokach et al., 1995; Mahan et al., 2004). Common sources of lactose are crystalline lactose, whey permeate, and dried whey, with whey products also providing a highly digestible source of amino acids. However, the addition of lactose products in the diet influences feed processing. The use of high levels of lactose in pelleted diets can increase friction during the pelleting process; and in meal diets can increase bridging and reduce flowability in bins and feeders.

Fat is not easily utilized by weanling pigs for growth performance. In the early post-weaning period, weanling pigs seem to require a more digestible fat source rich in unsaturated and short-chain fatty acids for an efficient energy utilization (Gu and Li, 2003). Vegetable oils like soybean oil and coconut oil are high quality sources of energy for weanling pigs (Weng, 2016), but cost often limits the use in nursery diets. Animal fat sources of good quality like choice white grease or beef tallow are usually more cost-effective to use in nursery diets. The addition of 3 to 4% fat is mainly used to improve the pelleting process of phase 1 diets with high levels of lactose.

Phase 2 diet

The phase 2 diet is typically fed to pigs from 15 to 25 lb of body weight. During this phase, feeding behavior is already established and, thus, diet complexity is reduced. The phase 2 diet is typically based on grain and soybean meal with low levels of specialty protein sources and lactose.

Soybean meal is often included at up to 20 to 24% of the diet. Other specialty protein sources often used in combination are fermented soybean meal, enzyme-treated soybean meal, or fish meal, among others. The level of lactose is reduced to around 7% lactose. Common sources of lactose are crystalline lactose, whey permeate, and dried whey, with whey products also providing a highly digestible source of amino acids. Fat begins to be utilized by the pig to improve growth performance and can be included at 1 to 3% in the diet. Common sources of fat are choice white grease or beef tallow, but other good-quality sources can be used if economically justifiable.

A phase 2 supplement is provided at KSU Premix & Diet Recommendations as an option instead of the addition of individual ingredients such as specialty protein and lactose sources in the diet.

Phase 3 diet

The phase 3 diet is typically fed to pigs from 25 to 50 lb of body weight. During this phase, feed consumption is the greatest and feed cost is critical, accounting for more than 50% of the total feed cost in the nursery.

The phase 3 diet is typically based on grain and soybean meal with no inclusion of specialty protein sources and lactose. Fat is utilized by the pig to improve growth performance and can be included at 1 to 3% in the diet. Common sources of fat are choice white grease or beef tallow, but other good-quality sources can be used if economically justifiable.

Example diets

Examples diets for phase 1, phase 2, phase 3, and intensive care are given at KSU Premix & Diet Recommendations.

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Amino Acid and Crude Protein Levels in Nursery Diets

Nursery pigs have a rapid growth rate and a high capacity for lean deposition relative to feed intake. Therefore, dietary amino acids and crude protein are essential to optimize growth performance in the nursery and have a significant influence on nursery diet cost. The practical approaches for determining dietary amino acids and crude protein levels in nursery diets are discussed in this fact sheet.

Amino acid requirements

The amino acid requirements of nursery pigs have increased significantly over time. As pigs have been growing faster with lower feed intake, the amino acid requirements as percentage of the diet have increased.

Current statistical modelling techniques have been applied to determine the dose-response to individual amino acids. Recently, the requirements of lysine (Graham et al., 2017; Nichols et al., 2018) and ratios for methionine and cysteine, threonine, tryptophan, isoleucine, valine, and histidine relative to lysine have been estimated for nursery pigs (Gonçalves et al., 2015; Jayaraman et al., 2015; Clark et al., 2017b,c; Kahindi et al., 2017; Cemin et al., 2018). By doing so, it is possible to determine the requirement to maximize growth performance and also predict the change in growth performance at a particular amino acid level. From a practical feeding standpoint, it is not always economical to feed diets at the amino acid levels to maximize growth performance. In many cases, it is more advantageous to feed diets with amino acid levels to achieve 95 to 99% of maximal growth performance than at levels to achieve 100% of maximal growth in the nursery (**Table 1**).

Table 1. Amino acid to lysine ratios for varying levels of growth performance of nursery pigs

Amino acid relative to lysine, %	95% of maximum performance	100% of maximum performance
Methionine	28	30
Methionine + Cysteine	56	60
Threonine	62	65
Tryptophan	19	21
Valine	67	72
Isoleucine	52	52
Histidine	30	31

Crude protein level

The crude protein level in nursery diets can pose an additional burden on weanling pigs. High-protein diets increase the quantity of undigested proteins and microbial fermentation in the hindgut, which predisposes the occurrence of post-weaning diarrhea (Heo et al., 2013). A practical approach is to feed low-protein, amino acid-fortified diets to decrease the burden imposed to the gut of weanling pigs. Typically, initial nursery diets contain up to 22% crude protein, but using feed-grade amino acids the crude protein level can be reduced to approximately 18%. The reduction in crude protein allows to minimize the inclusion of soybean meal that cause a hypersensitivity reaction in pigs, as well as the inclusion of specialty protein sources that increase diet cost. The low-protein diets should be supplemented with feed-grade amino acids to meet the amino acid requirements and support growth performance.

Lysine level

The lysine level influences the dietary crude protein content. A practical approach is to feed more moderate levels of lysine in initial nursery diets (1.35 to 1.40% SID Lys from 12 to 25 lb) that are typically composed of more expensive specialty protein sources. The lower lysine levels allow the reduction in crude protein and savings in diet cost. This approach leads to an excellent overall growth performance in the nursery as long as the lysine levels in late nursery diets are adequate (1.30 to 1.35% SID Lys from 25 to 50 lb). Thus, feeding lower lysine in early nursery and adequate levels in late nursery allows the reduction in crude protein and savings in diet cost while maintaining growth performance throughout the nursery period (Nemechek et al., 2018).

The dietary lysine level is also important to determine the level of other essential amino acids relative to lysine. Amino acid ratios are more critical in diets with lysine levels below the requirements than in diets with lysine at the requirements. Thus, using higher amino acid ratios in low-lysine diets is important to improve growth performance, whereas more moderate amino acid ratios can be used in diets with adequate lysine levels (Clark et al., 2017a).

Feed-grade amino acids

The use of feed-grade amino acids is key to meeting the amino acid requirements of nursery pigs, with accompanying reduction in dietary crude protein and savings in diet cost. The replacement of intact protein sources by feed-grade amino acids increases as feed-grade amino acids become available and economically justifiable. Currently, feed-grade lysine, methionine, threonine, tryptophan, and valine are all economical to include in nursery diets in the United States.

The maximum inclusion of feed-grade amino acids is often dictated by the ratio of lysine to crude protein and by the most limiting amino acid in the diet. Lysine to crude protein ratio is used to ensure a sufficient supply of nitrogen for synthesis of non-essential amino acids in low-protein, amino acid-fortified diets. For nursery pigs, up to a ratio of SID Lys:CP of 6.35 or total Lys:CP of 7.20 is recommended (Millet et al., 2018a,b). Also, the inclusion of feed-grade amino acids is determined by the next limiting amino acid in the diet, which can be isoleucine or histidine when all five first-limiting amino acids are available for feed-grade inclusion. However, low-protein diets fortified with the five first-limiting amino acids are typically able to meet the histidine requirements for nursery pigs (Cemin et al., 2018).

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Mineral Levels in Nursery Diets

Considering all the minerals supplemented in nursery diets, calcium, phosphorus, sodium, chloride, zinc, and copper are particularly important for adequate growth and health of nursery pigs. The requirements and practical levels of these minerals in nursery diets are discussed in this fact sheet.

Calcium and phosphorus

Calcium and phosphorus are essential for growth performance of nursery pigs. These minerals are involved in skeletal structure development and maintenance, lean tissue deposition, muscle contraction, and many other physiological functions. Phosphorus levels in nursery diets have typically a low safety margin because of environmental and economic concerns. Calcium levels, on the other hand, are typically high in nursery diets due to the unaccounted-for contribution of calcium from carriers, release from phytase, variability of calcium estimation in feed ingredients, and no environmental and economic concerns regarding calcium.

The accurate estimation of calcium and phosphorus requirements of nursery pigs is important to maximize growth performance, minimize phosphorus excretion in swine waste to the environment, and make savings in diet cost. Current statistical modelling techniques have been applied to determine the dose-response to calcium and phosphorus, as well as the ratio of calcium relative to phosphorus.

Calcium requirements

Calcium requirement estimates (**Table 1**) are typically expressed as total calcium. Total calcium accounts for the analyzed calcium content of ingredients. Recently, values for calcium digestibility in feed ingredients have been determined (González-Vega et al., 2015a,b; Merriman et al., 2016), allowing the requirements for digestible calcium to be estimated (González-Vega et al., 2016).

Nursery diets with excessive calcium levels have a severe negative impact on growth performance (González-Vega et al., 2016). The negative impact of excessive dietary calcium on growth performance is even more evident in diets with marginal or deficient phosphorus levels (González-Vega et al., 2016; Wu et al., 2018a).

The NRC (2012) calcium requirements for nursery pigs are very high, which may lead to an impact on growth performance when formulating diets to meet the calcium requirement estimates. A practical approach consists of maintaining adequate phosphorus levels and setting calcium levels relative to phosphorus, targeting between 1.10:1 and 1.25:1 total calcium to total phosphorus ratio or between 1:20 to 1.40:1 digestible calcium to digestible phosphorus ratio (González-Vega et al., 2016). By taking this approach, the NRC (2012) calcium requirement estimates can rather be used as an indication of maximum calcium levels in nursery diets.

Phosphorus requirements

Phosphorus requirement estimates (**Table 1**) are typically expressed as digestible phosphorus. Recently, the phosphorus requirements for nursery pigs have been determined by dose-response models, allowing for a more precise estimation of phosphorus levels to maximize growth performance and optimize economics while minimizing phosphorus excretion (Vier et al., 2017).

The phosphorus requirements of nursery pigs appear to be greater than the NRC (2012) recommendations of digestible phosphorus as a percentage of the diet (Vier et al., 2017; Wu et al., 2018b). The variation on phosphorus requirements depends on the goal, but typically the phosphorus requirements to optimize phosphorus retention is greater than to maximize growth (Vier et al., 2017; Wu et al., 2018b). A practical approach consists of maintaining phosphorus levels at approximately 140% and 130% of the NRC (2012) recommendations of digestible phosphorus for nursery pigs between 12 to 25 lb and 25 to 50 lb, respectively.

Table 1. Calcium and phosphorus requirement estimates for nursery pigs			
	Nursery pig weight, lb		
	12 to 15	15 to 25	25 to 50
Total calcium, %[1]	0.85	0.80	0.70
STTD calcium, %[2]	0.60	0.58	0.48
STTD phosphorus, %[3]	0.63	0.56	0.43

[1]From NRC (2012). Indication of maximum calcium levels in nursery diets. Set calcium by formulating to calcium:phosphorus ratio.
[2]From González-Vega et al. (2016).
[3]From Vier et al. (2017) and Wu et al. (2018b).

Calcium:phosphorus ratio

The calcium:phosphorus ratio greatly influences growth performance of nursery pigs and can even be more important than the absolute concentration of calcium and phosphorus. The ideal calcium:phosphorus ratio seems to be between 1.10:1 and 1.25:1 total calcium to total phosphorus ratio (Wu et al., 2018a) or between 1:20 to 1.40:1 digestible calcium to digestible phosphorus ratio (González-Vega et al., 2016).

Nursery diets with wide calcium:phosphorus ratios or excessive calcium and marginal or deficient phosphorus concentrations interfere with phosphorus absorption (Reinhardt and Mahan, 1986). Consequently, growth performance of nursery pigs is negatively affected by wide calcium:phosphorus ratios (González-Vega et al., 2016; Wu et al., 2018a). Diets with adequate phosphorus levels allow the calcium:phosphorus ratio to be on the upper range, with a decrease in growth performance around 1.9:1 to 2:1. However, diets with marginal phosphorus levels require a narrow calcium:phosphorus ratio (Reinhardt and Mahan, 1986; Qian et al., 1996; Wu et al., 2018a).

Phytase

Phytase is an enzyme that catalyzes the release of phosphorus from phytate. The addition of exogenous microbial phytase to nursery diets is a common practice to efficiently and economically enhance phosphorus utilization. Moreover, the use of phytase above conventional levels (500 to 1,000 FTU/kg) seems to have the potential to improve growth performance of nursery pigs beyond what is expected with adequate phosphorus levels (Zeng et al., 2014). The use of high levels of phytase is also becoming more common in nursery diets (Gourley et al., 2018; Laird et al., 2018).

More information about phytase is available at: Phytase in Swine Diets.

Sodium and chloride

Sodium and chloride are particularly important for nursery pigs. The minerals are involved in nutrient absorption, electrolyte balance, and regulation of pH. Salt is the most common source of sodium and chloride, but it is often not included in sufficient quantities to meet the requirements of sodium and chloride of nursery pigs. Sodium and chloride concentration are often overlooked in nursery diets because some commonly used ingredients contain high levels of sodium, particularly dried whey (approximately 1% sodium) and spray-dried plasma protein (approximately 3% sodium).

The requirements of sodium and chloride are greater for nursery pigs and abruptly decrease for grow-finish pigs. Recently, the requirements of sodium and chloride for nursery pigs have been determined (Shawk et al., 2018a,b) and indicated that the NRC (2012) requirement estimates are accurate (**Table 2**). Nursery diets need as much as 0.5 to 0.6% added salt to meet the requirements of nursery pigs. Nursery diets deficient in salt result in decreased growth performance due to reduced feed intake and poor feed efficiency (Shawk et al., 2018a,b).

Table 2. Sodium and chloride requirement estimates for nursery pigs			
	Nursery pig weight, lb		
	12 to 15	15 to 25	25 to 50
Sodium, %	0.40	0.35	0.28
Chloride, %	0.50	0.45	0.32

From NRC (2012) and Shawk et al. (2018a,b).

Dietary electrolyte balance

Dietary electrolyte balance represents the ratio of cations and anions in a diet and is important for acid-base status of pigs. The dietary ions that mostly influence electrolyte balance are sodium, chloride, and potassium. Dietary electrolyte balance is determined by the difference between cations and anions in the diet: Na + K - Cl. However, more comprehensive estimation of dietary electrolyte balance also takes into account the contribution of divalent ions, such as calcium, magnesium, sulfur, and potassium.

Traditionally, the optimal dietary electrolyte balance for pigs is reported to be approximately 250 mEq/kg (NRC, 2012). In nursery pigs, increasing dietary electrolyte balance to approximately 200 to 250 mEq/kg seems to have beneficial effects on growth performance (Lei et al., 2017; Jones et al., 2018).

Zinc and copper

Zinc and copper are trace minerals required at concentrations of 80 to 100 ppm and 5 to 6 ppm, respectively to meet the requirements of nursery pigs (**Table 3**). However, the addition of zinc and copper at quantities greater than the requirement exerts a beneficial effect on growth performance of nursery pigs (Liu et al., 2018). Greater quantities of zinc and copper are often referred as growth promoting or pharmacological levels.

Pharmacological levels of dietary zinc between 2,000 and 3,000 ppm is a common recommendation to initial nursery diets to reduce post-weaning diarrhea and improve growth performance (Hill et al., 2000; Shelton et al., 2011). These effects have been consistently demonstrated with dietary zinc provided as zinc oxide (ZnO) (Hill et al., 2001; Hollis et al., 2005; Walk et al., 2015), while zinc sulfate ($ZnSO_4$) has greater potential to induce toxicity (Hahn and Baker, 1993). Organic sources of zinc with greater bioavailability have not consistently demonstrated the same benefits as zinc oxide when organic zinc is added at lower levels (Hahn and Baker, 1993; Carlson et al., 2004; Hollis et al., 2005). However, pharmacological levels of zinc appear to interfere with calcium and phosphorus absorption, prompting the use of phytase or greater levels of calcium and phosphorus in nursery diets to ameliorate this effect (Blavi et al., 2017).

Pharmacological levels of dietary copper between 125 and 250 ppm are commonly used in the diet to enhance fecal consistency and improve growth performance of nursery pigs (Bikker et al., 2016). The most commonly used source of dietary copper is copper sulfate ($CuSO_4$) (Cromwell et al., 1998), but tribasic copper chloride (TBCC) is as effective as copper sulfate in promoting growth performance (Cromwell et al., 1998; Coble et al., 2017). Organic sources of copper with greater bioavailability, such as Cu-amino acid chelate, also seem to have the potential to influence growth performance (Pérez et al., 2011; Carpenter et al., 2018).

A typical recommendation is to use pharmacological levels of zinc in initial nursery diets fed to pigs up to 25 lb and then replace zinc by pharmacological levels of copper for the remaining nursery period (**Table 3**). Additive effects of using pharmacological levels of zinc and copper are not common (Hill et al., 2000), but might occur to some degree (Pérez et al., 2011). In diets with in-feed antimicrobials, the use of pharmacological levels of zinc or copper seems to have an additive effect in growth performance (Stahly et al., 1980; Hill et al., 2001).

The use of pharmacological levels of zinc and copper poses an environmental concern because of the greater excretion of minerals in swine waste and ultimately in the soil fertilized with swine manure (Jondreville et al., 2003). In addition, the implication of pharmacological levels of zinc and copper as a cause of increasing antimicrobial resistance is a rising concern (Yazdankhah et al., 2014). Therefore, regulations have been implemented in some countries restricting or prohibiting the use of zinc or copper as growth promoters. Thus, there is an appeal for prudent use of pharmacological levels of zinc and copper in swine production.

Table 3. Zinc and copper requirement estimates and recommended pharmacological levels for nursery pigs

	Nursery pig weight, lb		
	12 to 15	15 to 25	25 to 50
Requirement estimates[1]			
Zinc, ppm	100	100	80
Copper, ppm	6	6	5
Pharmacological levels[2]			
Zinc oxide, ppm[3]	3,000	2,000	-
Copper, ppm	-	-	up to 250

[1]From NRC (2012).
[2]From Hill et al. (2001) and Shelton et al. (2011).
[3]Pharmacological levels of zinc should only be used for short time. Maximum tolerance level of 1,000 ppm for long-term use.
- No recommendation of use.

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Fiber in Nursery Diets

Diets rich in dietary fiber generally have lower nutritive value for nursery pigs because digestive enzymes are not suited for degrading fiber. However, dietary fiber components seem to have beneficial effects on gut health and development, particularly to ameliorate post-weaning gut disorders. The concepts regarding fiber and the use of dietary fiber in nursery diets are discussed in this fact sheet.

Fiber definition

Carbohydrates are sources of energy in swine diets, but not all types of plant carbohydrates are able to be utilized by the pig. Plant carbohydrates are classified in storage carbohydrates (starch) and structural carbohydrates (non-starch polysaccharides). Starch is the main source of energy in swine diets and digestion in the upper gut produces glucose. Non-starch polysaccharides are the main structural carbohydrates of plant cell walls that resist digestion in the upper gut and are subject to fermentation by gut microflora in the hindgut to produce volatile fatty acids. All carbohydrates that resist digestion in the upper gut of pigs are defined as fiber (Kerr and Shurson, 2013).

Fiber classification and characteristics

Fiber is classified as soluble or insoluble based on fiber solubility in water. The fiber characteristics relevant to swine nutrition include fermentability, viscosity, and hydration. Natural fibrous feed ingredients are usually composed of both soluble and insoluble fiber.

Soluble fibers

Soluble fibers are more rapidly fermented in the hindgut and produce more volatile fatty acids, such as acetate, propionate, and butyrate, which are used as sources of energy to promote gut development (Montagne et al., 2003). Soluble fibers also promote a prebiotic effect by enhancing beneficial bacteria fermentation and production of volatile fatty acids while reducing gut pH to eliminate pathogens. The presence of soluble fibers increases digesta viscosity, which delays digesta passage rate, interferes with nutrient digestion, and predisposes proliferation and colonization of pathogens (McDonald et al., 2001). However, soluble fibers have better solubility, swelling capacity, water-holding capacity, and water-binding capacity that are important for digestion. Soluble fibers include pectins, gums, and β-glucans. Feed ingredients such as sugar beet pulp and citrus pulp have predominantly soluble fiber (Jha and Berrocoso, 2015).

Insoluble fibers

Insoluble fibers are relatively resistant to fermentation in the hindgut and do not contribute much to production of volatile fatty acids (Montagne et al., 2003). The presence of insoluble fibers increases fecal bulkiness and accelerates digesta passage rate, which prevents proliferation and colonization of pathogens (Wellock et al., 2008). Insoluble fibers include cellulose and hemicellulose. Feed ingredients such as wheat middlings, wheat bran, rice hulls, oat hulls, and distillers dried grains with solubles have predominantly insoluble fiber (Jha and Berrocoso, 2015).

Fiber analysis

The most common analytical methods to estimate fiber content in feed ingredients and feeds include crude fiber, acid detergent fiber (ADF), neutral detergent fiber (NDF), soluble and insoluble fractions of total dietary fiber (TDF), and non-starch polysaccharide (Kerr and Shurson, 2013). The fiber analytical methods measure several and sometimes different fractions of fiber. The ADF and NDF methods are widely used and quantify cellulose, hemicellulose, and lignin, which are insoluble fibers. Thus, the detergent methods provide an accurate estimate of insoluble dietary fibers, but soluble dietary fibers are not recovered in the analysis (NRC, 2012). The use of TDF method that categorize dietary fiber in soluble and insoluble fractions seems to provide the most useful analysis to determine the characteristics of fibrous feed ingredients (**Table 1**) for nursery diets (Agyekum and Nyachoti, 2017).

Table 1. Fiber composition of common ingredients used in nursery diets				
	Type of fiber, %		Detergent method, %	
Ingredient	Soluble	Insoluble	ADF	NDF
Barley[1,2]	5.4	9.7	5.8	18.3
Canola meal[1,2]	3.2	15.8	15.4	22.6
Corn[1,2]	0.9	6.0	2.9	9.1
Corn DDGS[1,3]	3.0	14.1	12.0	30.5
Oats, whole[1,3]	3.6	9.8	13.7	25.3
Oat hulls[4]	4.9	65.7	32.1	65.9
Rye[1,3]	3.7	8.4	4.6	12.3
Sorghum[1,2]	0.6	5.1	4.9	10.6
Soybean hulls[1,2]	10.0	45.0	41.6	59.4
Soybean meal[1,2]	3.9	12.6	5.3	8.2
Sugar beet pulp[1,3]	25.2	18.0	23.5	44.9
Sunflower meal[1,2]	5.2	29.4	23.0	30.2
Wheat[1]	2.3	6.8	3.6	10.6
Wheat bran[1,3]	2.5	23.8	11.0	32.3
Wheat middlings[1,3]	1.1	20.2	6.0	35.0

Adapted from [1]NRC (2012), [2]Brazilian Tables for Poultry and Swine (2017), [3]Jha and Berrocoso (2015), and [4]Jiménez-Moreno et al. (2016).

Fiber in nursery diets

The use of fiber in nursery diets is mostly related to the purpose of ameliorating post-weaning diarrhea. However, there are no firm recommendations of dietary fiber to confer health benefits on weanling pigs. In general, the use of insoluble fiber is preferred over soluble fiber in the immediate post-weaning period (Agyekum and Nyachoti, 2017) (**Table 2**).

Insoluble fibers accelerate digesta passage rate, which potentially prevents proliferation and colonization of pathogens and ameliorates post-weaning diarrhea. Soluble fibers have the opposite effect and potentially increase the risk of post-weaning diarrhea. The main issue with soluble fiber is the increase in digesta viscosity, which delays digesta passage rate and increases undigested nutrients, predisposing proliferation and colonization of pathogens.

Furthermore, weanling pigs would not benefit from the fermentation of soluble fibers in the hindgut because of the very limited capacity to ferment fiber at a young age. However, the use of soluble fiber in later nursery stages might be beneficial to promote gut health and development (Agyekum and Nyachoti, 2017).

The key to effectively utilize dietary fiber in the nursery consist of investigating dietary ingredients that deliver the appropriate fiber characteristics to address the main concern in the nursery, as well as understanding that fiber characteristics that ameliorate post-weaning diarrhea might not be the same as those to maximize growth rate (De Lange et al., 2010).

Table 2. Research evaluating the effects of different fiber sources on performance and gut health of weanling pigs					
Type of fiber	Basal diet	Challenge model	Response		Reference
			Performance	Gut health	
Soluble	Rice	*E. coli*	↓Daily gain	↑PWD incidence, ↑*E. coli* colonization, ↑digesta pH, ↑digesta viscosity	Hopwood et al. (2004)
Soluble	Rice	*E. coli*	No effect	↑PWD incidence, ↑*E. coli* colonization, ↔digesta pH	Montagne et al. (2004)
Soluble	Porridge oats, wheat, animal protein	*E. coli*	No effect	↓PWD incidence, ↔*E. coli* colonization, ↓digesta pH, ↑lactobacilli:coliform ratio	Wellock et al. (2008)
Insoluble	Corn, wheat, barley, soybean meal	*E. coli*	No effect	↓PWD incidence, ↓*E. coli* colonization, ↓coliforms, ↑short-chain fatty acids	Molist et al. (2010)
Insoluble	Rice, animal protein	None	No effect	↓ PWD incidence, ↑fecal consistency	Kim et al. (2008)
Insoluble	Corn, barley, soy protein concentrate	None	No effect	↓PWD incidence, ↓*E. coli* colonization, ↑short-chain fatty acids	Molist et al. (2011)

Adapted from Agyekum and Nyachoti (2017). Fiber diets are compared with non-antibiotic control diets.
PWD = post-weaning diarrhea. ↑ increase in response criteria, ↓ decrease in response criteria, ↔ no effect on response criteria.

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Feed Processing of Nursery Diets

Feed form, particle size, and pellet diameter are important characteristics that influence feed nutritional value, palatability, flowability, and ultimately growth performance of nursery pigs. The practical considerations of feed processing of nursery diets are discussed in this fact sheet.

Feed form

The common feed forms used in nursery diets are meal, pellets, and crumbles. Crumbles are made from whole pellets, which are broken into a smaller size in a roller mill. Typically, pellets or crumbles are preferred in initial nursery diets and either meal or pellets are often used in the following nursery diets.

Feed efficiency is typically improved with pellets compared to meal diets as a consequence of reduction in feed intake and/or less feed wastage with pellets (Groesbeck et al., 2009; Nemechek et al., 2015). However, the benefits of pelleting are greatly dependent on pellet quality (Stark et al., 1993). The greatest improvements in growth performance of nursery pigs are obtained by feeding high-quality pellets and minimizing the levels of pellet fines at the feeders to less than 20% (Nemechek et al., 2015). Meal diets in general require more feeder management to control feed wastage and improve feed efficiency compared to pellets.

Feed flowability is notably improved with pellets compared to meal diets. Feed flowability is a concern in diets with specialty proteins and lactose, as is often the case of initial nursery diets (Carney et al., 2005). Meal diets with high inclusion of specialty ingredients can increase bridging and reduce flowability in bins and feeders, which can easily limit feed availability to weanling pigs. Thus, initial nursery diets that often contain high inclusion of specialty ingredients are typically pelleted or crumbled. However, high levels of lactose in pelleted diets can increase friction during the pelleting process and potentially scorch the ingredients. The addition of 3 to 4% fat in initial nursery diets is often recommended to enhance lubrication of the pellet die and prevent heat damage.

The pelleting temperature is crucial to preserve the nutritional value of ingredients. Applying excessively high temperatures during pelleting can potentially scorch the ingredients or initiate Maillard reactions, thereby affecting feeding value and growth performance of nursery pigs (Steidinger et al., 2000). The negative effects on feeding value and growth performance of nursery pigs have been observed with pellet conditioning temperatures above 170°F (Steidinger et al., 2000).

Meal diets are commonly used in the nursery following the pelleted initial nursery diets. Compared to pellets, meal diets have less expensive feed manufacturing costs.

Particle size

Particle size is important for digestibility of nutrients and energy and for growth performance of nursery pigs (Rojas and Stein, 2017). In meal diets, a reduction in grain particle size to approximately 600 microns improves digestibility of nursery diet and growth performance of nursery pigs. However, grinding grains below 500 microns affects feed flowability and palatability (De Jong et al., 2014; Gebhardt et al., 2018). The fine grinding of grains reduces feed intake with no improvement in feed efficiency, thereby affecting growth performance of nursery pigs (De Jong et al., 2014; Bertol et al., 2017; Gebhardt et al., 2018). However, in pelleted diets, fine grinding of grains to approximately 350 microns does seem to improve growth performance of nursery pigs (De Jong et al., 2014).

Pellet diameter

Pellet diameter is generally assumed to be important for feed intake of nursery pigs. However, nursery pigs seem to be very adaptable to a variety of pellet diameters (Edge et al., 2005; van den Brand et al., 2014). The common belief that small diameter pellets improve the ability of weanling pigs to apprehend and swallow feed is not sustained (Clark et al., 2016). Actually, feeding large pellets can increase feed intake of weanling pigs during the first week in the nursery compared to feeding small pellets (0.5 inch compared to 0.125 inch pellet diameter; Clark et al., 2016).

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Key Concepts of a Successful Grow-Finish Nutritional Program

There are many possible ways to design a grow-finish nutritional program. Understanding the relationship between nutrition and growth in this phase of production is important for success. Key concepts that are discussed in this fact sheet are: defining production goals and objectives, establishing nutrient requirements, understanding ingredients, space availability, and herd health.

Defining Production Goals and Objectives

Before a nutritional program can be developed, the production system's goals and objectives must be clearly defined. This is especially important in the grow-finish period as many different nutritional and management strategies can be employed to create a successful program. Factors such as facility size, space availability, and marketing schedules will be important to consider as these all play a role in how a production system will design their nutritional program.

Different economic measurements can be used to determine economic success and this can differ between production systems. Five different economic measurements of feed programs include evaluating total dietary cost, feed cost per unit of gain, income over feed cost (IOFC), income over feed and facility cost (IOFFC) and income over total cost (IOTC). An understanding of these different measurements is critical to evaluating economic success and opportunity within a grow-finish nutritional program. Total dietary costs and feed cost per unit of gain can be used as economic tools when the focus is to reduce variable costs. Whereas IOFC and IOFFC are accurate methods to determine profitability as they consider total revenue, dietary costs, and facilities costs. Income over total cost (IOTC) is another method to determine profitability, but this calculation must include an understanding of all costs (ex. antibiotic usage, vaccines, labor, transportation, etc.). Accuracy of IOTC must include an understanding of these costs which may be less accurate or unavailable.

The measurement best suited for evaluating the economic output of a grow-finish nutritional program should consider potential influence of dietary changes on performance and marketing strategy. Changes in nutrient levels and ingredient composition of the diet can influence grow-finish live and carcass performance. Space constraints and seasonal effects on pig performance can dictate the number of pigs reaching ideal market weight and utilization of pig spaces. This can vary based on production system and change throughout the year. Marketing strategies will have to be adjusted in periods of low growth rates to optimize economic return.

Nutrient Requirements

Establishing the nutrient requirements of grow-finish pigs during different stages of production is important. To establish nutrient requirements, an understanding of growth curves related to changes in protein deposition and feed intake changes throughout the grow-finish period is needed. The development of these growth curves and tissue accretion rates must be farm specific as factors such as genetics and environment will impact the growth curves. Furthermore, grow-finish pigs go through different phases of growth as they increase in BW and age. The relationship between energy intake and maximum protein deposition rates of pigs plays an important role in dictating growth and establishing the energy level in a diet that maximizes economic output. Once the optimal energy level is determined, a lysine:calorie ratio should be established to determine the lysine level. After the lysine level is determined, the other essential amino acids relative to lysine can be established to avoid deficiencies and imbalances that can limit growth. A calcium:phosphorous ratio can then be established. Finally, customized feed budgets can be created to ensure the correct amount of feed is being delivered to meet nutrient requirements and optimize the production systems performance objectives.

Understanding Ingredients

When considering diet formulation in a grow-finish nutritional program, the availability of ingredients will dictate diet formulation and influence total feed cost. The nutrient content of these ingredients is important because different ingredients will impact grow-finish performance and carcass composition in different ways. Understanding how ingredients impact pig performance is vital to developing a successful grow-finish nutritional program.

Assigning accurate nutrient values and maintaining an up-to-date database is key for successful diet formulation.

Inaccurately assigning nutrient values to ingredients can cause deviations in predicted growth performance and reduce economic opportunity. Ingredient values can be obtained through database management sources. Periodic sampling of available ingredients or new ingredients should be conducted to ensure the analyzed ingredient profile closely matches assigned values. More information on assigning nutrient values or ingredient sampling procedures.

Alternative feedstuffs can often be used to increase economic return. Dried distillers grains with solubles (DDGs), wheat middlings, and bakery meal are examples of such alternative feedstuffs that are utilized in diet formulation as replacements for corn and soybean meal. Understanding the nutrient composition of these ingredients is important before considering implementation in diet formulation (Woyengo et al., 2014). Example calculations for determining relative nutrient values of ingredients are provided in the KSU General Nutrition principles.

Manufacturing processes can affect the nutrient composition of alternative feedstuffs. Dried distillers grains with solubles can be variable in composition based on the production process utilized in ethanol production. The oil content, heating time and temperature of wet distillers grains, and amount of solubles added back during the production process contribute to variability in the nutrient content of DDGS and differences between product from different ethanol plants (Fabiosa, 2008). Bakery meal can also inherently be variable in nutrient content due to the different food ingredients used to create the bakery meal and carriers included to improve flow ability (Liu et al., 2018).

Nutrient composition of the ingredients being used in diet formulation should be thoroughly understood as differences in nutrient content of ingredients can influence pig performance and carcass composition. Utilizing ingredients with high fiber contents can negatively influence digestibility of energy from the diet and decrease pig performance (Noblet and Le Goff, 2001). Addition of fat to the diet could be considered to alleviate some of these issues with high fiber ingredients such as DDGS or wheat middlings, but the fatty acid composition of the fat source could negatively impact carcass fat composition. Moreover, utilization of ingredients in diet formulation with high unsaturated fat and/or high fiber content compared to corn can negatively influence carcass fat composition and carcass yield, respectively. These examples emphasize the importance of understating the nutrient content of ingredients being used in diet formulation. When designing a grow-finish nutritional program, accurate assignment of nutrient values help better predict performance and optimize economic output.

Space Availability

Fixed Time vs. Fixed Weight

Pigs can be marketed on either a constant weight or constant time basis. A constant weight marketing strategy is employed in periods of high growth rate where space (time in the barn) does not become limiting. A constant days marketing strategy is employed in periods where pig space is limited (ex. during low growth rate). The economics of each marketing strategy must be evaluated as the value of gain versus value of days in the barn can differ. Under constant day marketing strategies, improving the gain through nutritional or management strategies can potentially improve economic output per pig even if the cost of feed per lb of gain is increased. Under constant weight marketing strategies, improving growth rate may not improve economic output, as reducing the facility cost by reducing the number of days to reach the optimal marketing weight may not offset the increases in feed cost per lb of gain (Table 1 and 2). Although, pig space can be limited even with high growth rate especially in times when production systems are undergoing expansion. Therefore, economic evaluations should be continuously conducted as dietary or management changes can affect economic output in different marketing situations.

Seasonality

It is well documented that pigs experience seasonal variations in performance due to temperature changes (Figure 1).

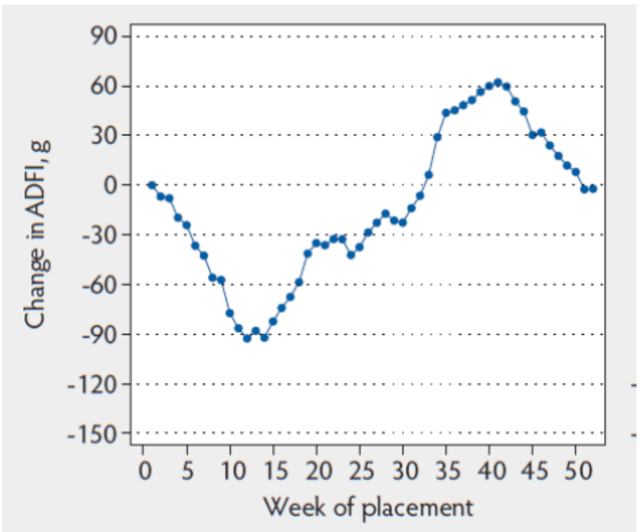

Figure 1. Week of placement effects on grow-finish ADFI (Wu et al., 2019).

Heat stress is a major component of the seasonal variation in performance as pigs will reduce voluntary feed intake in response to high temperatures (Renaudeau et al., 2011). The reduction in feed intake is associated with a decrease in gain. Due to the slower growth rate in pigs fed during summer months, different nutrition and marketing strategies should be employed compared to pigs fed in fall and winter months (Wu et al., 2019). During the summer months, a constant day marketing strategy could potentially be employed. Because pigs will take more time to reach optimal market weights, space becomes a constraint. During winter months, a constant weight strategy could possibly be employed because growth rates are generally increased in these months and space might not be limiting. The increased growth rate in winter months will allow pigs to reach an optimal marketing weight in fewer days. Economic evaluations should be conducted to determine the correct marketing strategy in different parts of the year. Applying a seasonality curve to predict ADFI and ADG in an effort to develop marketing projections in different times of the year should be considered due to the seasonal differences in performance.

Dietary Energy

Feed intake differences due to seasonality or genetics can lead to reductions in grow-finish pigs' energy consumption. This can impair growth performance because of the relationship between energy intake and growth. The genetic line being used in the production system affects energy intake as pigs selected for low feed intakes potentially could respond to increasing levels of dietary energy while pigs selected for higher feed intakes may not. In periods of heat stress, feed intake and thus energy consumption will be decreased which will impair growth. In an effort to promote energy intake, producers can potentially increase energy concentration in the diet. Ingredients such as fats and oils are used as they have a lower heat increment and contain greater energy than cereal grains. Increasing energy density of the diet will increase total dietary costs and the proportional improvement in daily gain and feed efficiency should justify the increase in feed costs.

An economic evaluation of increasing energy density of the diet should be considered before employing this strategy in a grow-finish nutritional program (Table 1 and 2). Table 1 shows an example economic evaluation of added dietary energy based on a constant day marketing strategy. This strategy is employed where growth rate is limited during summer heat stress or for genetic lines selected for low feed intake. This would cause pigs to not achieve ideal market weights on a fixed time and gain is valued in these situations. It can be observed that increasing the energy of the diet through added fat will increase total dietary costs, but also improves average daily gain (ADG) and feed efficiency (F/G). Because of the improvement in growth performance, the value of gain is increased. Although feed costs are increased, the increase in amount of gain achieved during the fixed time increases IOFFC when adding fat to the diet.

Table 2 shows an example economic evaluation of added dietary energy based on a constant weight marketing strategy. This strategy is employed in situations where growth rate is not limited such as winter or in genetic lines selected for higher feed intakes. Since gain is not being limited in these situations, time to reach ideal market weights becomes the most important factor. With the increase in dietary energy through the addition of fat, F/G is improved and the number of days needed for pigs to achieve ideal market weights is reduced. In this example, the reduction in facility costs with the reduced numbers of days on feed does not offset the increases in feed cost per lb of gain and thus decreases profitability on an IOFFC basis.

Herd Health

The type, duration, and spread of a health challenge can cause large losses in economic opportunity due to declines in performance and increased economic input to control the disease (Holtkamp et al., 2013; Schulz and Tonsor, 2015; Valdez-Donoso et al., 2018). It is known that the requirement for energy and some amino acids are increased in a health challenge situation, but these changes in requirements are minimal (de Ridder et al., 2012). The activation of the immune system in a health challenge reduces feed intake and increases protein degradation. This causes limitations in protein accretion and reduces growth performance in pigs. Therefore, in a health challenge situation, it is not recommended to alter diet formulation by increasing nutrient content of the diet.

Soybean meal level in diets has recently been investigated as a dietary strategy to help alleviate growth performance issues in health challenge situations. This is thought to be due to soybean meal containing isoflavones that can potentially exhibit antiviral, antioxidant, and anti-inflammatory properties against viruses (Andres et al., 2009). While some data shows benefits of increased soybean meal inclusion in health challenged situations, the response is variable and more research is needed to understand and validate the mechanism behind the potential improvement (Boyd et al., 2010; Schweer et al., 2018).

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Table 1. An example on how to determine the economic value of added dietary fat in a constant day marketing strategy

Assumptions:	
Diets without added fat	**Diets with 3% added fat**
- Feed cost: $160/ton or $0.08/lb	- Feed cost: $175/ton or $0.088/lb
- Market price/cwt = $0.60	- Market price/cwt = $0.60
- Initial BW: 55 lb	- Initial BW: 55 lb
- F/G: 2.80	- F/G: 2.60
- ADG: 1.80 lb	- ADG: 1.85 lb
- Fixed days in grow-finisher = 125	- Fixed days in grow-finisher = 125
- Final live BW: 55 lb + (1.80 lb × 125 d) = 280 lb	- Final live BW: 55 lb + (1.85 lb × 125 d) = 286 lb
Calculations:	
Feed cost = $160/ton or $0.080/lb	Feed cost = $175/ton or $0.088/lb
Feed cost per lb of gain = 2.80 × $0.080 = $0.224/lb gain	Feed cost per lb of gain = 2.60 × $0.088 = $0.229/lb gain
Income over feed cost = revenue – feed cost	Income over feed cost = revenue – feed cost
Gain value = (Final live BW – starting BW) × market price/cwt = (280 lb – 55 lb) × $0.60 = $135.00	Gain value = (Final live BW – starting BW) × market price/cwt = (286 lb – 55 lb) × $0.60 = $138.60
Feed cost = Feed cost per lb gain × total lb gained = $0.224/lb gain × (280 lb – 55 lb) = $50.40	Feed cost = Feed cost per lb gain × total lb gained = $0.229/lb gain × (286 lb – 55 lb) = $52.90
Income over feed cost = Gain value – Feed cost = $135.00 – $50.40 = $84.60/pig	Income over feed cost = Gain value – Feed cost = $138.60 – $52.90 = $85.70/pig

Table 2. An example on how to determine the economic value of added dietary fat in a constant weight marketing strategy

Assumptions:	
Diets without added fat	**Diets with 3% added fat**
- Feed cost: $160/ton or $0.080/lb	- Feed cost: $175/ton or $0.088/lb
- Initial BW: 55 lb	- Initial BW: 55 lb
- Market price/cwt = $0.60	- Market price/cwt = 0.60
- Facilities cost/d =$0.10	- Facilities cost/d = $0.10
- F/G: 2.80	- F/G: 2.60
- ADG: 1.80 lb	- ADG: 1.85 lb
- Fixed live market weight = 285 lb	- Fixed live market weight = 285 lb
Calculations:	
Number of days to 285 lb = (Market Weight – Starting Weight)/ ADG	Number of days to 285 lb = (Market Weight – Starting Weight)/ ADG
Number of days to 285 lb = (285 lb – 55 lb) / 1.80 lb = 128 days	Number of days to 285 lb = (285 lb – 55 lb) / 1.85 lb = 124 days
Facility cost = Total days × Facilities cost/day = (128 d) × ($0.10) = $12.80	Facility cost = Total days × Facilities cost/day = (124 d) × ($0.10) = $12.43
Feed cost = $160/ton or $0.080/lb	Feed cost: $175/ton or $0.088/lb
Feed cost per lb of gain = 2.80 × $0.08 = $0.224/lb gain	Feed cost per lb of gain = 2.60 × $0.088 = $0.229/lb gain
Income over feed cost = revenue – feed cost	Income over feed cost = revenue – feed cost
Gain value = (Final live BW – starting BW) × market price/cwt = (285 lb – 55 lb) × $0.60 = $138.00	Gain value = (Final live BW – starting BW) × market price/cwt = (285 lb – 55 lb) × $0.60 = $138.00
Feed cost = Feed cost per lb gain × total lb gained = $0.224/lb gain × (285 lb – 55 lb) = $51.40	Feed cost = Feed cost per lb gain × total lb gained = $0.238/lb gain × (285 lb – 55 lb) = $52.90
Income over feed and facilities cost = Gain value – Feed cost – facility cost = $138.00 – $51.40 - $12.80 = $73.80/pig	Income over feed and facilities cost = Gain value – Feed cost – Facility Cost = $138.00 – $52.90 -$12.43 = $72.67/pig

Protein and Fat Deposition

A relationship exists between protein deposition and energy intake in regard to grow-finish growth performance. This relationship changes in different stages of grow-finish as the pig becomes heavier and understanding this change allows for the development of nutrient requirements.

Energy for Maintenance vs. Growth

Dietary energy is utilized for maintenance and growth. Maintenance energy requirements are the amount of energy needed for basal metabolic functions and to maintain body weight (Velayudhan et al., 2015). Under normal growing conditions, after maintenance needs are met, pigs will prioritize lean tissue deposition and then direct nutrients towards fat deposition (Bikker et al., 1996). Therefore, a relationship exists between energy supply above maintenance requirements and protein and fat deposition rates.

Energy Intake and Protein Deposition Relationship

Two different phases of growth exist in the grow-finish period that describes the influences of dietary energy intake on protein deposition. Early in the growing period, a linear relationship exists between dietary energy intake and protein deposition (Campbell and Taverner, 1988; Bikker et al., 1994). This relationship reveals that increasing dietary energy intake under non-limiting amino acid conditions will linearly increase protein deposition in growing pigs up to their upper limit to protein deposition (PD_{max}) and then plateau (Figure 1). This indicates that pigs are in an energy dependent period of growth. Body protein increases linearly with energy intake until the Pdmax is reached (Bikker et al., 1996). Increases in energy intake above that needed for Pdmax will increase the rate of lipid deposition and can result in fatter carcasses and poorer feed efficiency.

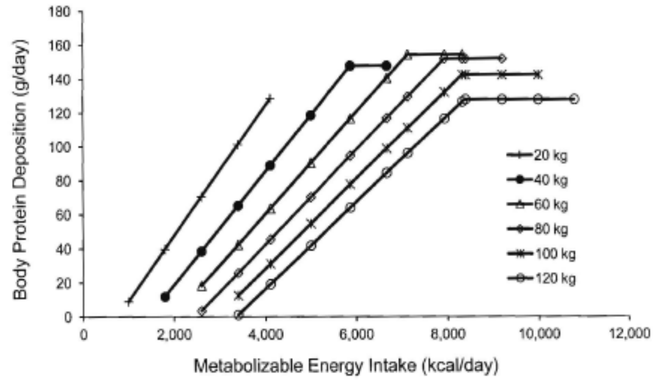

Figure 1. Relationship between protein deposition (g/d) and ME intake (kcal/day) in growing gilts at different bodyweights (NRC, 2012).

Although increasing dietary energy intake can increase protein deposition in growing pigs, the physical capacity for feed intake limits dietary energy intake and thus protein deposition. Conversely, increasing dietary energy intake in pigs during the late finishing phase of production can lead to increases in lipid deposition versus protein deposition (Figure 2).

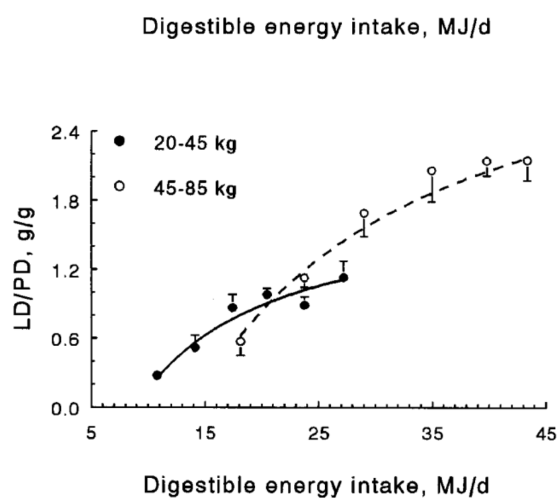

Figure 2. Lipid deposition to protein deposition ratio (g/g) at different energy intakes in 2 different weight ranges of pigs (Bikker et al., 1996).

This observation can be explained in the changes in body composition as a pig ages. The rate of lipid accretion rapidly increases as pigs enter the late finishing phase of production while lean tissue accretion rates stay relatively constant (Figure 3).

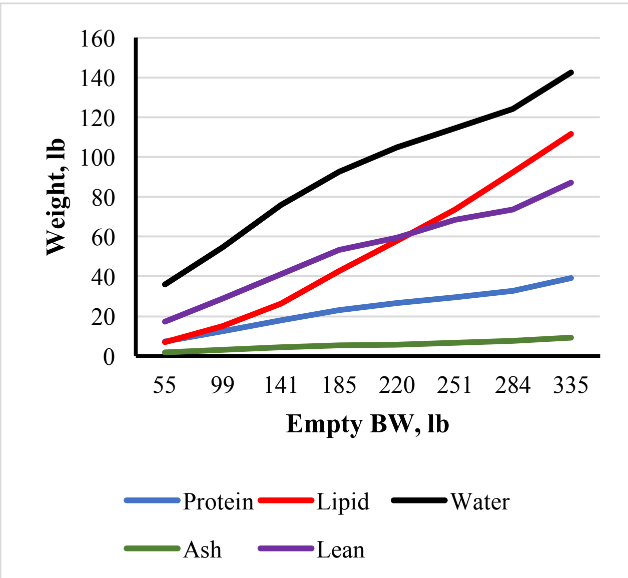

Figure 3. Changes in chemical body composition with increasing body weight (Adapted from Wagner et al., 1999).

This phase of growth is considered the protein dependent phase because energy intake no longer limits protein deposition.

Limiting energy intake in early phases of the grow-finish period can negatively affect protein deposition and growth, but overfeeding energy in later periods can lead to increases in lipid accretion. Understanding this helps aid in determining the number of dietary phases used in the nutritional program, the weight ranges of these dietary phases, and nutrient requirements in an effort to maximize protein deposition and optimize economic success.

Gender Differences

Gender should be taken into consideration when developing nutrient recommendations as energy intake and protein deposition between barrows and gilts differ (Figures 4, 5).

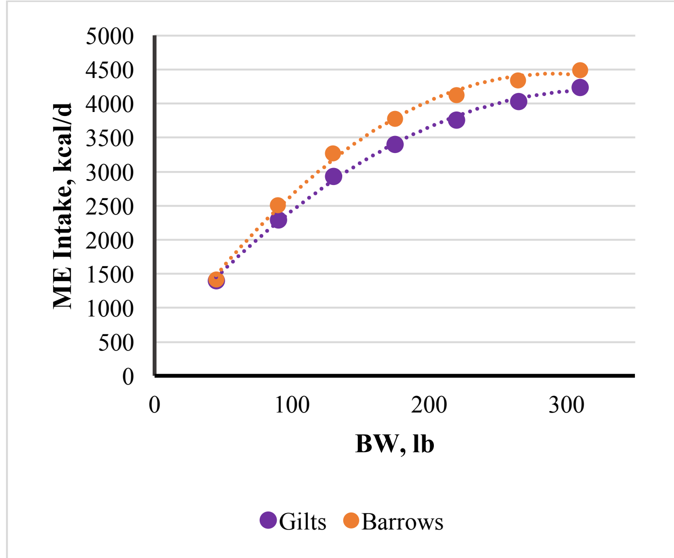

Figure 4. Typical daily ME intakes of barrows and gilts between 45 and 310 lb (Adapted from NRC, 2012).

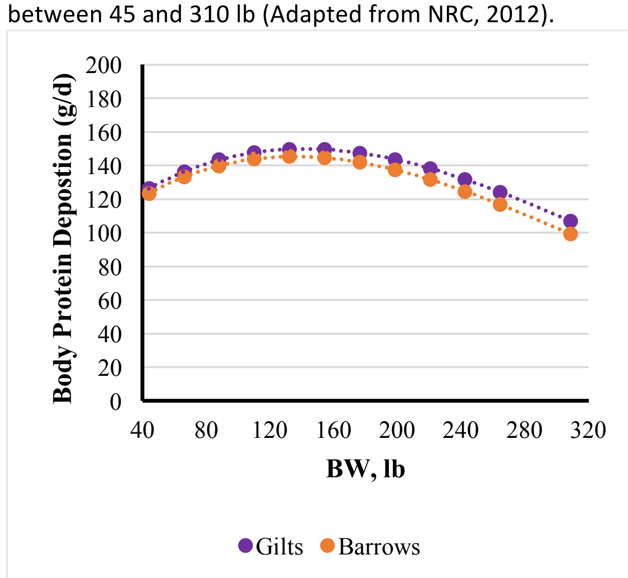

Figure 5. Typical whole-body protein deposition curves in gilts and barrows between 40 and 320 lb (Adapted from NRC, 2012).

Metabolizable energy (ME) intake is greater in barrows in the grow-finish stage versus that of gilts while the protein deposition rates are greater in gilts than barrows.

Genetic Differences

Understanding Pd_{max} allows for a relationship to be established between energy intake and body protein deposition at various stages of the grow-finish period in a production system (de Lange, 2001). Genetic line being used should be taken into consideration as different genotypes exhibit different protein accretion rates at different body weights (Figure 5).

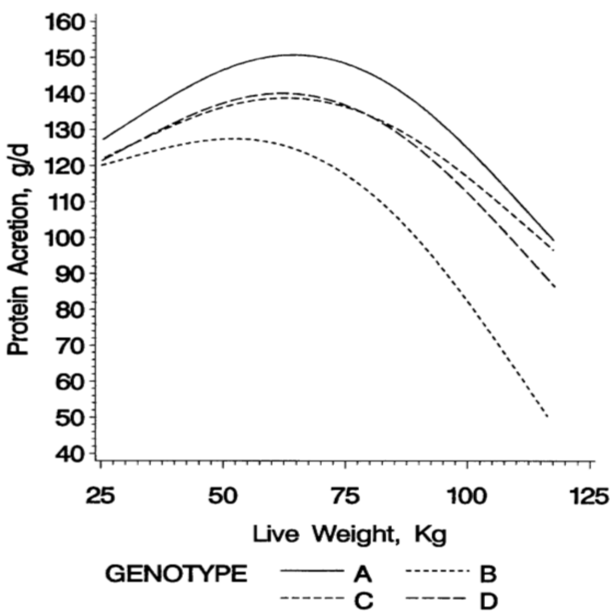

Figure 5. Differences in protein accretion rate between 4 different genetic lines (Schinckel and de Lange, 1996).

Different genetic lines will reach PD_{max} at different points in the grow-finish period. After Pd_{max} is reached, rates of protein accretion decline. In general, genetic lines selected for high protein accretion will reach Pd_{max} at heavier weights and the rate of protein accretion decline will be less than genetic lines selected for average or low protein accretion. Furthermore, under commercial conditions, grow-finish pigs can be exposed to numerous environmental stressors. Genetic lines will respond differently to environmental stressors such as high stocking density, heat stress, disease, etc. and this can significantly limit expression of their true genetic potential for Pd_{max}. Due to this, producers should understand the environmental conditions of their production system so that they can better understand their specific protein accretion rates and its relationship with energy intake to establish nutrient requirements.

In summary, a relationship exists between energy intake and protein deposition. Limiting energy intake in early phases of the grow-finish period can negatively affect protein deposition and growth, but overfeeding energy in later periods can lead to increases in lipid versus protein accretion. Producers should also understand that differences in the expression of this relationship exist between gender and genetic lines and must be considered when developing nutrient requirements.

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Establishing Phase Feeding Programs and Feed Budgets

Understanding the rate at which pigs grow in a specific production system provides more accurate determination of nutrients and feed amounts. Understanding growth curves, how to develop growth models, and establishing customized phase feeding programs will be discussed in this factsheet.

Growth Curves

To aid in development of feeding programs, producers should understand the changes in growth rate of pigs during the grow-finish period. When body weight is plotted versus age, the typical growth curve follows a linear shape (Figure 1). After plotting BW versus age, producers can calculate ADG at different timepoints and depict ADG versus weight (Figure 2). It can be observed that pigs undergo rapid periods of growth in the early stages, reach a maximum, and decline at heavier bodyweights. Growth curves should be developed as average daily gain versus body weight to develop nutrient requirements. As the growth rate slows, less nutrients are required to support maintenance and growth. This allows for more accurate diet formulation by preventing excess nutrients being supplied from the diet. Furthermore, producers should understand that the point at which grow-finish pigs reach their maximum growth rate can vary based on genetic line used. Different genotypes will exhibit different rates of protein accretion and this will change the point at which protein deposition is maximized.

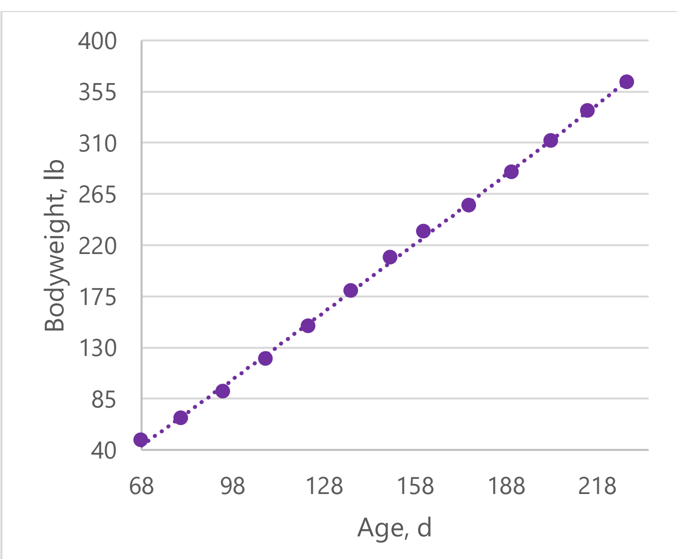

Figure 1. Diagram of a typical growth curve of body weight vs age for growing-finishing pigs from birth until market (Adapted from Lerner, 2019).

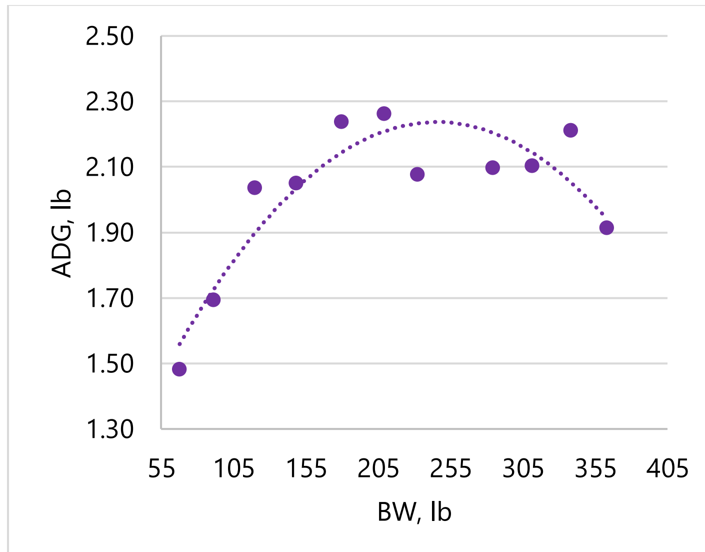

Figure 2. Diagram of a typical growth curve of ADG vs body weight for growing-finishing pigs from weaning until market (Adapted from Lerner, 2019).

Growth and Feed Intake Curve Model Development

Development of grow-finish growth models can be achieved by either using reference modelling equations provided from sources such as the NRC (2012) or using farm-specific data. Both methods can be used in an effort to understand the nutrient requirements of grow-finish pigs at varying stages of production. Knowing these nutrient requirements will allow for customization of feed budgets for individual farms and estimate the optimal marketing weight to optimize economic success.

The first step in developing growth models to predict performance is to correctly quantify farm specific model inputs needed to develop these models (de Lange et al., 2001). The specific model inputs needed are dependent on whether a reference equation is utilized to generate growth curves or a farm specific growth curve is developed. If a reference equation is utilized, the model inputs needed are mature bodyweight, growth rate, age at maximum growth rate, energy intake and energy required for maintenance (NRC 2012, Rostagno, 2017). Although these reference equations are accurate in predicting growth rate, these equations were developed under ideal growing conditions and may not best represent farm specific growth rates.

Inputs for the reference equations required for these models may not be available in production systems. Thus, production systems may want to develop their own specific growth model. This allows for the accurate determination of the upper limit to protein deposition (Pd_{max}) for a specific farm. Accurate determination of PD_{max} is important as it aids in estimating the amino acids required for actual protein deposition being achieved. Growth and tissue accretion curves can be developed that are specific to a production system through serial scanning (Smith et al., 1999;). From these scanning methods, tissue accretion and growth curves can be developed that allow producers to determine nutrient requirements at different stages of the grow-finishing period.

Once daily nutrient requirements are determined from acquired protein deposition curves and a relationship is established between energy intake and protein deposition, estimates of feed intake should be determined. It is important to accurately estimate feed intake as this will determine the optimal level of dietary nutrients needed to support observed growth rates. If body protein, lipid rates, and maintenance energy are known inputs, reference equations are available from the NRC (2012) to determine daily energy to support observed growth rates. If these inputs are unavailable, production systems can develop their own actual growth and feed intake curves. To develop these curves, 3 to 4 pigs of each gender from at least 6 different pens must be weighed at least 5 different timepoints throughout the grow-finish period. At each of these timepoints, feed disappearance is measured. Average daily feed intake is then calculated between these different timepoints and plotted against bodyweight to determine actual feed intake. This actual feed intake curve can be compared to reference intake curves to understand where nutritional or management practices can be improved to optimize growth (de Lange et al., 2001).

Once growth and feed intake curves are established, a phase feeding program can be developed based on the various weight ranges and growth rates to provide adequate nutrients for protein deposition and minimize excessive lipid deposition.

Phase Feeding

Phase feeding is a strategy where multiple diets are fed to a group of pigs based on feed budgets or weight ranges to closely meet the pigs nutrient requirement. It is generally understood that grow-finish pigs nutrient requirements decrease over the entirety of the grow-finish period and phase feeding is employed to meet these changing nutrient demands (Figure 1).

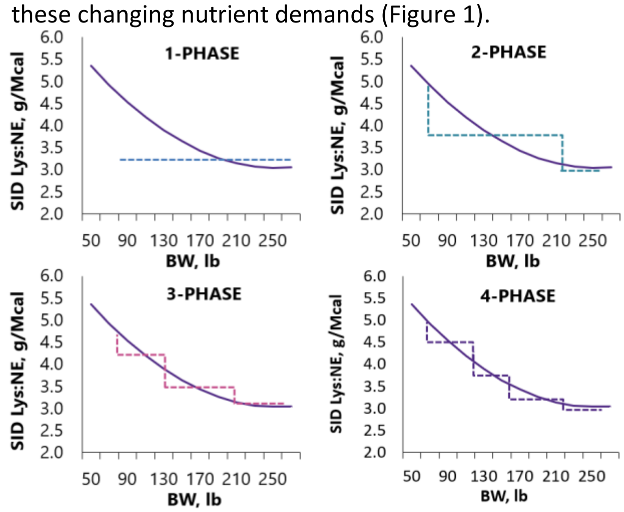

Figure 1. Diagram of phase-feeding strategies (dash line) in relation to estimated lysine requirement (solid line) expressed as a ratio of SID lysine to net energy (Menegat et al., 2019).

Nutrient requirements must be accurately estimated as the pig progresses through the grow-finish period to optimize growth performance and economic output. In the past, we have recommended 5 to 6 dietary phases from 50 lb to market weight. This is to closely meet the pig's changing nutrient requirements and reduce nutrient excretion in waste. However, recently it has been shown that these 5 to 6 phase programs may not provide greater economic return than a 3 to 4 phase system (Menegat et al., 2019). In some cases where pigs might be underfed, compensatory growth is achieved by pigs either increasing voluntary feed intake or improving feed efficiency. To achieve compensatory growth, pigs require adequate, if not greater amino acid concentrations in the finishing period to exhibit the potential benefits (Whang et al., 2003). As long as diets fed prior to pigs being marketed meet or exceed the pigs' requirement, compensatory growth can occur and recapture lost performance due to diets being below their requirement in earlier phases (Main et al., 2008; Menegat et al., 2019). However, if the amino acid restriction is too long or severe and the compensatory period too short, compensatory growth may not occur. The number of dietary phases and nutrient fortification should be carefully evaluated with a nutritionist.

On the other hand, decreasing the number of diets fed can provide benefits to the feed manufacturing process by improving feed mill efficiency and simplifying mill logistics (Moore et al., 2013). Therefore, if feed intake and initial BW are accurately determined in a production system, simplifying phase-feeding programs can optimize growth performance and economics of a feeding program.

Establishing Feed Budgets

Once the number of phases are determined in a feeding program, customized feed budgets within the dietary phases can be established. Using customized feed budgets based on feed efficiency, a specific amount of feed is delivered to a group of pigs to gain a predetermined amount of weight. This avoids changing diets based on visual observation which may under- or over-estimate the group's actual weight. It also avoids errors made when changing diets based on a set time period. Therefore, making diet changes based on feed efficiency will be the most accurate method of matching diets with the appropriate weight range.

The inputs needed to design a customized feed budget includes feed efficiency for the specific system and the beginning and ending weight of the desired weight range. The number of dietary phases fed can vary, but based on close-out information, the pounds of feed required for a specific weight range can be determined. This amount is then multiplied by the number of pigs fed and the total amount of feed required can be estimated (Table 1).

Feed budgets can also be matched with either mixer capacity, the amount a feed truck can deliver, or bin capacity at the site. For example, if the delivery truck can hold 24 tons of feed, diets can be changed on 24 ton increments to avoid partial deliveries which will reduce feed mill and delivery efficiency.

If data necessary to develop customized feed budgets is not available, a calculator is available that helps producers develop a feed budget program. To utilize the calculator, the producer inputs their beginning weight, ending weight, and feed efficiency. Then, the producer determines the ending weight for the desired number of phases. The pounds of feed per pig will then be calculated for each phase. Table 2 provides an example of a 5 phase feeding program.

Improvements in feed efficiency will decrease the amount of feed needed for each phase. This can be observed in the differences of amount of feed needed between barrows and gilts using the same number of phases and weight ranges within these phases (Table 2).

Using feed budgets based on feed efficiency allows for more accurate determination of the amount of feed needed for a group of pigs to gain a predetermined amount of weight to avoid excesses or deficiencies in nutrients being provided.

In summary, understanding changes in growth rate of grow-finish pigs allows for more accurate development of growth curves. Reference equations exist to aid in the development of growth curves, but producers can develop growth curves that are specific to their production system. This allows for more accurate determination of nutrient requirements at different stages of the grow-finish period and allows for development of a phase feeding program specific to a production system.

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Table 1. An example on how to create a customized feed budget based on estimated F/G and weight range	
Assumptions:	Calculations
Weight Range: 50 to 90 lb Estimated F/G = 2.25:1 Total Gain: 40 lb Number of pigs being fed: 600	Feed per pig = (Total lb of gain per pig) × Estimated F/G = 40 × 2.25:1 = 90 lb/feed per pig Tons of feed to be delivered = (Total lb of feeder per pig × total number of pigs) = 90 × 600 = 54,000 lb (27 tons)

K-State Grow-Finish Feed Budget Program

Gilt Feed Budget		
Closeout Feed Efficiency		
Initial wt	Final wt	F/G
50	285	2.7
Initial wt	Final wt	lb/pig
50	90	**78**
90	130	**90**
130	180	**130**
180	230	**150**
230	285	**187**

Barrow Feed Budget		
Closeout Feed Efficiency		
Initial wt	Final wt	F/G
50	285	2.9
Initial wt	Final wt	lb/pig
50	90	**84**
90	130	**97**
130	180	**140**
180	230	**161**
230	285	**201**

Mixed Sex Feed Budget		
Closeout Feed Efficiency		
Initial wt	Final wt	F/G
50	285	2.8
Initial wt	Final wt	lb/pig
50	90	**81**
90	130	**94**
130	180	**135**
180	230	**155**
230	285	**194**

Table 2. Example of a customized feed budget program based on estimated F/G and body weight ranges (KSU Feed Budget Calculator).

Energy

In designing a grow-finish nutritional program, it is important to understand the responses to changing dietary energy and the impact on economic decisions. This fact sheet will discuss dietary energy effects on growth performance, formulating on a nutrient to calorie ratio, energy sources and quality, as well as fiber.

Influence on Growth Performance

Energy System

Ingredient energy values and the dietary energy system utilized must be constantly evaluated to ensure energy costs are minimized. This is because different energy systems provide varying accounting of the differences in energy utilization derived from ingredients based on their composition. The NE system is the most accurate in estimating the energy value of ingredients in a diet and the influence of dietary energy on growth performance. Because of this, diet formulation should be conducted with the net energy system due to the differences in measuring energy losses from digestion and absorption. This will aid in evaluating the different effects dietary energy can have on pig growth and carcass performance.

Growth Performance

Understanding how energy influences maintenance and tissue accretion is important as this will change throughout the grow-finish period and dictate growth performance.

Historically, increasing the energy concentration of the diet has shown to improve pig growth performance (De la Llata et al., 2001). Although, this response is dependent on the pigs' phase of growth. Producers must understand how pigs respond to dietary energy in the grow-finish phase of production as the growth performance response to increasing energy in the diet can change based on genetics, health status, environmental temperature, and stocking density.

Early in a pig's life, lean growth and, thus, daily gain, is limited by feed intake. As pigs grow and feed intake increases, lean deposition eventually reaches a plateau, where further increases in energy intake don't increase growth (Figure 1). In earlier periods where feed intake is lower, a linear response in lean growth can be observed as energy intake increases. Thus, pigs will respond to the increasing dietary energy with increased growth. In situations where feed intake is high and pigs are on the plateau for lean growth, a diminishing response to increasing energy is observed. Whether pigs are on the linear or plateau portion of the response to energy depends on the genetics, health status, and feed intake of the pigs. Producers must understand where the plateau occurs in order to determine optimal energy level in the diet.

Furthermore, increasing the dietary energy concentration in a diet increases feed costs and potentially has negative consequences on carcass composition. An economic evaluation should be conducted to determine if the improvements in pig growth performance are greater than the increased dietary costs associated with the added dietary energy.

Energy Sources and Quality

Fats and oils are commonly added to grow-finish diets. This is because these ingredients contain approximately 2.25 times more energy and the energy within these ingredients are highly digestible compared to cereal grains. The most common forms of fats used in diet formulation are animal fats derived from the rendering industry while the most common forms of oils used are extracted from seeds (link to general nutrition guide on energy sources). When considering the inclusion of a fat or oil source to increase energy density of the diet, fat quality should be evaluated as it can influence digestibility and energy value. Furthermore, it should be understood that grow-finish pigs will deposit fat in a similar fatty acid profile as the dietary fat or oil source being supplemented to the diet (Gatlin et al., 2002). This is important as fats and oils differ in their degree of saturation and this will effect grow-finish carcass composition and pork quality. This should be understood as it may limit the fat source that can be used in diet formulation in an effort to avoid discounts for carcasses and optimize economic success.

Nutrient to Calorie Ratio

Nutrient to calorie ratios must be considered when setting the energy level in diet formulation. This is because the energy content of the diet will dictate the amount of feed consumed by growing-finishing pigs. In general, increasing energy concentration of growing-finishing pigs diets will result in reductions in voluntary feed intake. The reductions are the results of pigs adjusting their voluntary feed intake to meet their daily nutrient demands while maintaining a constant energy intake (Nyachoti et al., 2004). But it should be understood that essential nutrients such as amino acids and phosphorous in the diet must be adjusted with this increasing energy concentration of the diet. Because voluntary feed intake will be reduced, daily intake of these essential nutrients will also be decreased. This decrease in nutrient intake may limit growth performance and thus the nutrient:calorie ratio must be adjusted accordingly. Therefore, to maintain a constant level of intake of these essential nutrients, the concentrations of these nutrients must be increased simultaneously with increased energy concentration in the diet.

The importance of this nutrient to calorie ratio can be observed when determining the lysine level in diet formulation. It is well established that lysine is the first limiting amino acid in swine diets as it is the most important substrate for generating body protein (Liao et al., 2015). This relationship shows that increasing lysine intake with energy intake will improve protein deposition and weight gain (Chiba et al., 1991; Marcal et al., 2017).

Fiber

Fiber concentration of ingredients should be considered as greater concentrations can decrease the digestibility of energy through decreased lipid digestibility (Wilfart et al., 2007). Although, the negative relationship between energy digestion and fiber inclusion may be improved with increasing pig age and weight due to increased retention time through the digestive process. This allows for greater inclusion rates of fiber in grow-finish diets (Le Goff et al., 2002). However, the type of fiber utilized in diet formulation should also be considered as this can affect nutrient digestibility to different degrees. While both insoluble and soluble fiber decrease energy digestibility, inclusion of moderate to high levels of insoluble fiber (i.e., wheat middlings and dried distillers grains with solubles [DDGs]) ingredients decrease the digestibility of energy toa greater extent than soluble fiber ingredients (i.e., sugar beet pulp and citrus pulp; Owusu-Asiedu et al., 2006).

Growth Performance

The effects of fiber utilization on grow-finish growth performance should be considered when evaluating the dietary energy level and use of high-fiber ingredients in diet formulation. It has been reported that including high levels of DDGS in grow-finishing diets does not affect growth performance compared to a corn-soybean meal diet, but reductions in performance have been observed in other studies (Linneen et al., 2008; Nemechek et al., 2015; Coble et al., 2017). The inconsistency in the response to DDGS could be attributed to the large variability in its nutrient composition. Dried distillers grains with solubles commonly have greater concentrations of crude fat, CP, and fiber than corn. The energy content varies with changes in oil and fiber components (Peterson, 2007; Graham et al., 2014). Graham et al. (2014) developed an equation based on oil content of DDGs sources to predict their NE content (Figure 2). Therefore, NE values should be used to provide more accuracy in diet formulation and an equation is available to aid in prediction of NE values of DDGs sources.

Fiber Withdrawal Strategies

Because reductions in performance can be observed when feed contains high fiber ingredients, nutritional strategies can be developed to alleviate these negative responses. An effective strategy that has been utilized is switching from high fiber diets to low fiber diets (fiber withdrawal) shortly before marketing. Withdrawing high fiber ingredients from the diet and switching to a corn-soybean meal diet has been observed as an effective tool at recapturing growth performance and carcass yield losses before marketing (Asmus et al., 2014; Graham et al., 2014; Soto et al., 2017). The benefits from the withdrawal strategy can be attributed to the energy and fiber relationship on feed intake. Feeding high fiber ingredients increases gut fill due to the increased dietary bulk density and can limit energy intake (Whittemore, 2001). Furthermore, reduced carcass yield is observed when high fibrous diets are fed throughout the grow-finish phase as the intestinal contents at harvest are increased (Asmus et al., 2014; Coble et al., 2017). By switching from a high fiber diet to corn-soybean meal diets, carcass yield can be improved. This diet switch should be done with the last diet before final marketing. However, the response to fiber withdrawal depends on the level of fiber in the diet and duration of the withdrawal (Lerner et al., 2018). An economic evaluation must be conducted to determine if withdrawing high fiber ingredients from the diet before market will optimize economic success.

The inclusion of high fiber ingredients should be considered in growing-finishing pig diets as they can help alleviate high feed costs; however, the negative effects on growth performance as well as carcass performance should be considered. An economic evaluation should be conducted when using high fiber ingredients in diet formulation to determine appropriate inclusion rates and feeding duration.

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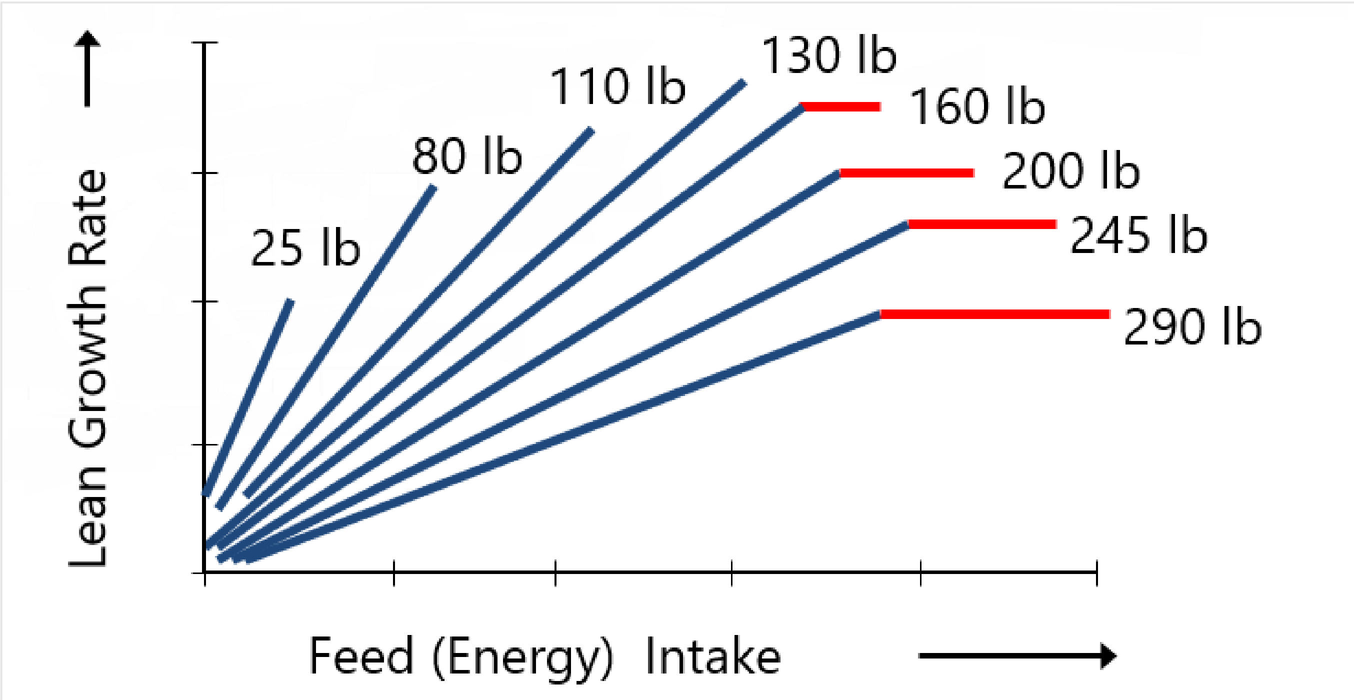

Figure 1. Influence of energy intake on lean growth rate. Lines indicate lean growth rate in relation to feed intake at different pig body weights.

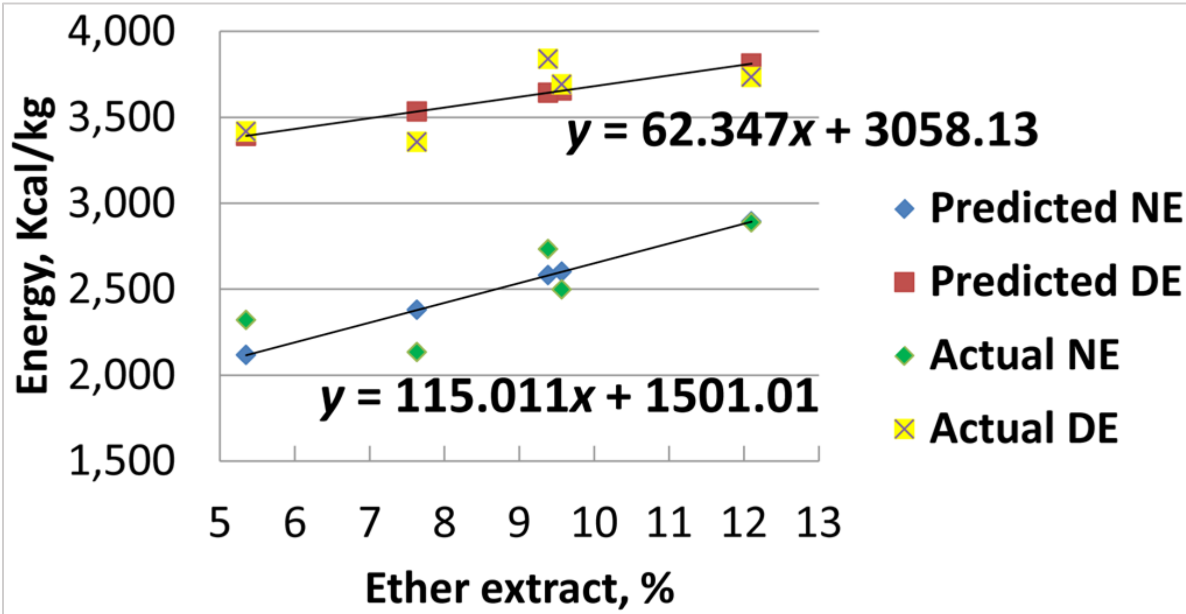

Figure 2. Predicted and measured DE and NE values of distillers dried grains with solubles sources varying in oil content (as-fed basis) using equations created in stepwise regression. DE (*n* = 5), adjusted R_2 = 0.41; NE (*n* = 5), adjusted R_2 = 0.86 (Graham et al., 2014).

Amino Acids

Establishing farm specific amino acid requirements is an essential step in diet formulation that is based on understanding the growth of the pigs. How to determine amino acid requirements, reasons amino acid requirements change in the grow-finish period, and feed-grade amino acid usage in diet formulation will be discussed.

Determining AA Requirements

Establishing the dietary concentration of amino acids that meet the growth and maintenance needs for grow-finishing pigs is vital to establishing a profitable nutrition program. The pig's amino acid requirements can be acquired from internal production system research, growth rate and feed intake data, protein accretion curves at the farm level, genetic companies, or research data conducted at the university level. Advantages and disadvantages exist in each of these methods in terms of their accuracy in estimating amino acid requirements and cost to obtain the data.

Once the dietary energy level is determined, a lysine:calorie ratio needs to be set. The lysine requirement is expressed as a ratio to energy because changes in dietary energy will affect feed intake and/or growth rate.

Differences in feed intake, environmental conditions, and production goals can affect the decision on which lysine:calorie ratio to use. Thus, it is best to determine the lysine requirement within the specific production system. Protein deposition curves can also be utilized to estimate lysine requirements. By using these curves, producers can understand the changes in protein deposition rates of grow-finish pigs as they approach market weight and better estimate lysine requirements. If this data is not available, lysine requirements can be derived from growth rate and feed intake data. In general, grow-finish pigs require approximately 20 g standardized ileal digestible (SID) lysine / per kg of gain (Rostagno, 2017). After determining the lysine requirement, the other AA ratios relative to lysine can be determined.

AA requirement changes in the grow-finish period

Rate of protein deposition is the main determining factor in amino acid requirements. With increasing body weight, protein deposition decreases relative to feed and energy intake, therefore decreasing the dietary lysine level required to support growth. However, as the pig becomes heavier, maintenance requirements increase relative to those used for growth (Moughan, 2003). This relationship explains why requirements for amino acids involved in maintenance functions, like threonine and sulfur-containing amino acids (methionine and cysteine) increase as ratios relative to lysine as body weight increases. Furthermore, tissue turnover rates relative to protein deposition change with increasing age which explains why the ratios of threonine and methionine and cysteine relative to lysine increase but tryptophan ratios are similar throughout the grow-finish period (Mahan and Shields, 1998).

Establishing the requirements of the other amino acids relative to lysine is important as amino acid imbalances in the diet can occur. Imbalances in amino acids are caused by an amino acid being supplied at levels lower or higher than what is required to optimize growth. These imbalances can potentially lead to reduced feed intake and poor growth performance (Baker, 2004). Recommendations for minimum amino acid requirements in the grow-finish phase are provided (Table 1).

Feed-Grade Amino Acids

Feed-grade amino acids have become more readily available and economical to use in diet formulation. Feed-grade lysine, methionine, threonine, tryptophan, valine, and isoleucine are currently commercially available for swine diets. Increased cost of intact proteins and increased availability of feed-grade amino acids has led producers to use more low-protein, feed grade amino acid fortified diets. Low protein diets offer the opportunity to reduce nitrogen excretion in swine waste, a benefit for the environment.

If not formulated correctly, low-protein, feed grade amino acid fortified diets can result in an overall fatter carcass compared to that of feeding a higher crude protein diet (Hinson et al., 2009; Li et al., 2016). This is the result of feed-grade amino acids replacing a lower energy ingredient (soybean meal) with a higher energy ingredient (corn) in the diet. The energy system being utilized in diet formulation should be understood when formulating with feed-grade amino acids as energy utilization is attributed differently based on ingredient composition. In the ME and DE systems, energy in the diet is overestimated when protein ingredients are included while the NE system takes utilization inefficiency of energy from protein into account. Cereal grains, like corn, increase in the diet when feed-grade AA are used and the NE system can capture this difference in energy utilization more accurately than the DE or ME systems (van Milgen et al., 2001; Li et al., 2018). The NE system will more accurately represent how the energy is being utilized by the pig with the inclusion of feed-grade amino acids to avoid increased fat deposition.

When feed-grade amino acids are supplemented in low crude protein diets to maintain amino acid ratios, growth performance is similar to that of feeding high crude protein diets (Kerr et al., 2003; Molist et al., 2016). There are questions on whether there is a minimum level of crude protein or soybean meal that should be included in late-finishing diets. It has been observed that reducing dietary crude protein level below 13% with feed-grade amino acids reduces growth performance of finishing pigs (Soto et al., 2019). More knowledge about requirements for nonessential amino acids or ratios between essential amino acids is needed to allow for lower crude protein diets to be fed to late finishing pigs without negatively impacting growth performance.

The use of feed-grade amino acids in grow-finish diets is an effective way to reduce feed costs and nitrogen excretion, but producers must consider the situations where high levels of feed-grade amino acid supplementation may not be appropriate to avoid decreases in growth and carcass performance.

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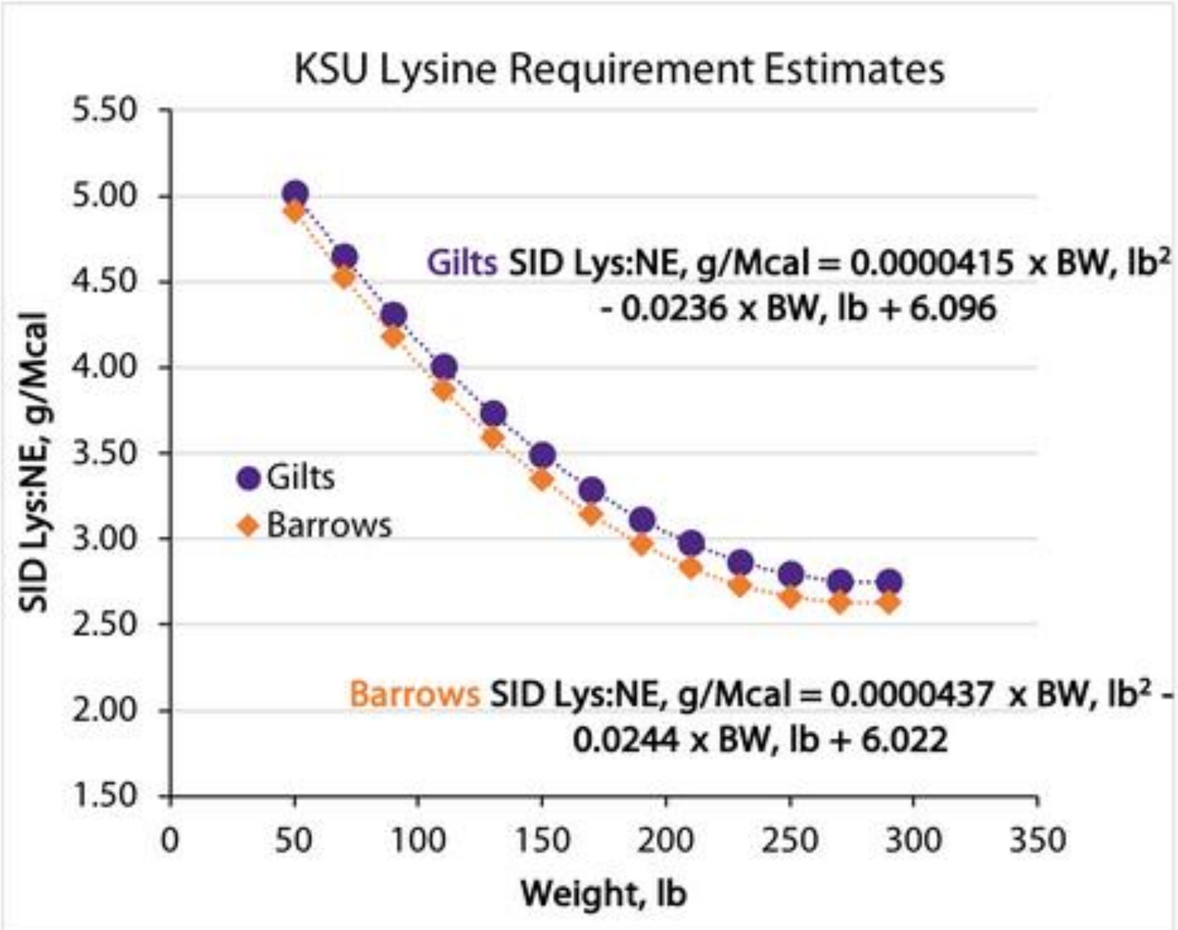

Figure 1. KSU Lysine recommendations for grow-finish pigs .

Table 1. Minimum standardized ileal digestible lysine and amino acid to lysine ratios for growing-finishing pigs

	Growing-finishing pigs weight range, lb			
SID amino acids[1]	55 to 130	130 to 175	175 to 220	220 to 285
Lysine, %[2]	1.08	0.88	0.78	0.70
Amino acid to lysine ratio, %[3]				
Methionine	28	28	28	28
Methionine + Cysteine	56	56	57	58
Threonine	62	62	63	64
Tryptophan	18	18	18	18
Isoleucine	52	52	52	52
Valine	68	68	68	68

[1]Minimum levels based on the NRC (2012) ingredient loading values.

[2]Minimum lysine levels containing a diet with 1,150 kcal NE/lb.

[3]Minimum ratios to achieve approximately 95% of maximum growth performance. Minimum ratios of threonine, tryptophan, isoleucine, and valine may need to be increased depending on diet formulation.

Vitamins and Minerals

Vitamins and minerals are involved in metabolic functions required for growth, development, and maintenance. Because of inadequate concentrations and/or limited bioavailability of some essential vitamins and minerals provided from ingredients within a swine diet, supplementation is required to meet their requirements. The importance of formulating to correct phosphorous, Ca:P ratio, sodium and chloride, and vitamin and trace mineral concentrations are discussed in this fact sheet.

Importance of Phosphorous in Diet Formulation

Phosphorous (P) is the second most abundant mineral in the body. Besides bone mineralization, phosphorous is involved in protein accretion and energy metabolism. Deficient levels can inhibit skeletal development and growth. Phosphorous is often the third most expensive diet component and excess levels can lead to increased diet costs. Exogenous phytase is commonly added to grow-finish diets to increase the availability of phosphorous which decreases the amount of mono or di-calcium phosphorus in the diet.

Assigning Phosphorous Values in Diet Formulation

Phosphorous values can be assigned to ingredients as either total, available, or digestible. Total P values are rarely used in diet formulation as it does not accurately represent the amount available for use by the pig and can cause deficiencies. Available P is determined through the use of a slope-ratio assay method, in which a standard source of phosphorus is given a value of 100% and the availability of P in an ingredient is estimated as a relative percentage to the standard source. Although the slope-ratio method seems to be more accurate to estimate availability of P, there is a concern about assuming 100% availability in the standard source. Also, determining the available P value for each ingredient is generally expensive. Therefore, digestible P provides a better estimate of the amount of P being digested and absorbed. Digestible P can be expressed several ways. Two common ways are apparent digestible and standardized total tract digestibility. The standardized value is preferred because it accounts for endogenous loss of P.

Phosphorous Formulation Considerations

A digestible P:calorie ratio should be utilized when formulating diets as dietary energy concentration will influence the amount of feed consumed. Thus when using a standard ratio, the dietary level of P can be adjusted to account for changes in feed intake. Also, as feed efficiency and lean growth improve, the dietary P requirement concentration will increase (Vier et al., 2017). Furthermore, when using phytase, P release values should be used to ensure accurate P levels are being formulated.

Ca:P Relationship

Both P and Ca are required for bone mineralization. Since Ca and P share an absorption pathway, excess dietary Ca can have an antagonizing effect on P digestion and absorption (Létourneau-Montminy et al., 2012). Therefore, a Ca:P ratio is commonly used in diet formulation to ensure excess Ca does not interfere with phosphorous absorption. Calcium supplementation is low cost and if not limited in diets, least cost formulation will allow excess Ca into the diet to lower cost. This can lead to a wide Ca:P ratio that may lead to reductions in grow-finish pig performance especially when P is below the requirement (Stein, 2016). When diet P concentrations are adequate, increasing the Ca:P ratio can improve growth performance of grow-finish pigs (Vier et al., 2017). Furthermore, Ca:P ratios should be formulated on a digestible basis. If digestible Ca values are not available, the ratio should be formulated on analyzed Ca:analyzed P ratio.

In summary, digestible P values should be utilized when formulating a Ca:P ratio in diets and the amount of digestible P being provided should be adequate to meet P requirements.

Sodium and Chloride

Sodium and chloride are directly involved in nutrient absorption, electrolyte balance, and regulation of pH. Dietary supplementation of these minerals is essential as sodium and chloride are low in most cereal grains used in swine diets. Salt or sodium chloride is the most common source supplemented to swine diets to meet their requirements. The sodium and chloride requirements for grow-finish pigs decrease abruptly from the nursery stage. A typical grow-finish diet has 7 to 10 lb per ton added salt which is well beyond their sodium and chloride requirements.

Trace Mineral Supplementation

Copper, iron, iodine, manganese, selenium and zinc are typically supplemented in grow finish diets through a premix to meet the dietary requirements as some trace minerals have low bioavailability in feed ingredients. However, some trace minerals are included above the pig's requirement at growth promoting levels. High levels of copper (up to 250 ppm) can be supplemented to promote growth of finishing pigs. This effect seems to be greater in younger pigs compared to older pigs (Davis et al., 2002; Carpenter et al., 2017; Coble et al., 2017). Furthermore, in periods where high levels of protein deposition are observed, such as when ractopamine is included in diets, data has shown that the zinc requirement is increased (Paulk et al. 2015). Therefore, increased levels of supplemental zinc (up to 100 ppm) can be supplemented to support the increased protein deposition. When using increased levels of copper or zinc, care must be exercised so as not to lead to toxicity. Environmental factors should also be considered.

Vitamin Supplementation

Because some vitamins are not produced by pigs or have low bioavailability in feed ingredients, vitamins are routinely supplemented to grow-finish diets. While the NRC (2012) recommends vitamin requirements which include amounts from feed ingredients (total vitamin levels), standard practice is to only consider vitamins provided by the premix (added vitamin levels). Also, vitamins contained in the premix are typically formulated above NRC (2012) recommendations to provide a margin of safety that accounts for low bioavailability in ingredients, differences in daily feed intakes, or degradation due to storage and feed processing (Flohr et al., 2016).

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Table 1. Vitamin and Mineral recommendations for growing-finishing pigs

	Growing-finishing pig weight, lb			
	55 to 130	130 to 175	175 to 220	220 to 285
Total calcium, %[1]	0.66	0.59	0.52	0.46
STTD calcium, %[2]	0.49	0.43	0.38	0.33
STTD phosphorus, %[2]	0.38	0.33	0.29	0.26
Available phosphorus, %[2]	0.32	0.28	0.24	0.21
Total Ca:STTD P[2]	1.74	1.79	1.79	1.77
STTD Ca:STTD P[2]	1.30	1.30	1.31	1.27
Na, %[3]	0.24	0.17	0.17	0.17
Cl, %[3]	0.40	0.31	0.31	0.31
Trace Minerals[4]				
Zinc, ppm	110	92	73	55
Iron, ppm	110	92	73	55
Manganese, ppm	33	28	22	17
Copper, ppm	17	14	11	8
Iodine, ppm	0.30	0.25	0.20	0.15
Selenium, ppm	0.30	0.25	0.20	0.15
Vitamins[4]				
Vitamin A, IU/ton	2,250,000	1,875,000	1,500,000	1,125,000
Vitamin D, IU/ton	900,000	750,000	600,000	450,000
Vitamin E, IU/ton	24,000	20,000	16,000	12,000
Vitamin K, IU/ton	1,800	1,500	1,200	900
Vitamin B12, mg/ton	18	15	12	9
Niacin, mg/ton	27,000	22,500	18,000	13,500
Pantothenic Acid, mg/ton	15,000	12,500	10,000	7,500
Riboflavin, mg/ton	4,500	3,750	3,000	2,250

[1]Indication of maximum calcium levels for each phase. Calcium level determined by formulating to calcium:phosphorus ratio developed from Vier (2017).
[2]Indication of phosphorous levels in grow-finish diets to optimize growth performance developed from Vier (2019).
[3]Sodium and chloride recommendations based on corn-soybean meal diet with 10 lb/ton inclusion of salt in 50 to 130 lbs and 7 lb/ton inclusion for all other weight ranges.
[4]Added levels from KSU vitamin and trace mineral premixes provided at 0.15% of the diet.

Feed Processing

Feed processing is an important component of optimizing a grow-finish nutritional program. Factors such as grain particle size, feed form, and pellet quality can influence nutrient digestibility and feed efficiency. Producers also need to consider changes in diet flowability, changes in bulk density, incidence of gastric ulcers, and costs associated with changes in feed processing. The practical considerations of feed processing in grow-finish diets are discussed in this fact sheet.

Particle Size

Particle size of cereal grains is an important consideration as it can influence nutrient digestibility and thus growth performance. For every 100 micron reduction in particle size, down to 300 microns, a ~1% improvement in F/G can be observed due to the improved nutrient digestibility. Reducing the particle size of corn and other ingredients to approximately 550 to 600 microns (when measured with a flow agent) improves the energy digestibility but does not influence the digestibility of phosphorous or amino acids (Mavromichalis et al., 2000; Rojas and Stein, 2015; Saqui-Salces et al., 2017). Diet form should also be considered because reducing grain particle size below 500 microns in mash diets can negatively affect feed flowability (Gebhardt et al., 2018). Reducing particle size also can potentially increase incidence of gastric ulcers leading to decreased growth performance and increased mortality (Ayles et al., 1996; Millet et al., 2012).

In summary, reducing particle size improves F/G due to an improvement in energy digestibility and the recommended particle size of finishing diets is 500 - 600 microns.

Feed Form

Feed is typically fed in grow-finish diets in meal and pelleted form. Feeding pelleted diets in the grow-finish period results in improvements in feed efficiency and average daily gain. The improvement in feed efficiency partly due to decreasing feed wastage and increasing nutrient digestibility (Ball et al., 2015; Nemechek et al., 2015; 2016).

The type of feeder used may also have an effect on whether mash or pelleted diets should be fed to growing-finishing pigs. Pigs fed a meal diet using a wet/dry feeder had improved average daily gain and increased feed intake compared to when a conventional dry feeder was used (Bergstrom et al., 2012). However, the improvement in growth performance with a pelleted diet is dependent on pellet quality as the amount of fines present can influence the magnitude of growth response (Myers et al., 2013). Furthermore, the pelleting process exposes feed ingredients, specifically vitamins and enzymes, to high temperatures which can reduce their stability and efficacy (Svihus and Zimonja, 2011; Truelock et al, 2018). Therefore, heat-stability of enzymes and vitamins should be considered when pelleting swine diets.

Pellet Quality

Pellet quality will affect the level of growth performance improvement. Poor quality pellets are associated with more fines which can lead to more feed sorting and feed wastage and decreased performance (Myers et al., 2013). It is estimated that a 1% change in feed efficiency will be observed with every 10% change in pellet fines (Stark, 1993; Amornthewaphat et al., 2000; Nemechek et al., 2015). Pellet quality can be improved through diet formulation adjustments such as including higher amounts of protein and starch-based products; fat application post-pelleting and not in the mixer, manipulation of the pelleting process such as increasing conditioner temperature or retention time, increasing water content, or using an expansion process (Loar and Corzo, 2011; Lundblad et al., 2012).

Producers should consider the changes in pig performance, diet flow ability, incidence of gastric ulcers, and manufacturing costs when evaluating feed processing methods. Feed cost per lb of gain and income over feed costs should be considered in the economic decision process.

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Gilt Development

A successful gilt development program is vital to a production system because it has a direct effect on reproductive performance and sow lifetime productivity. While many management practices such as boar exposure and estrus detection affect reproductive performance, a solid nutrition program is also required. This fact sheet will focus on bodyweight targets and nutritional program recommendations from weaning to first breeding.

Nutritional Program Recommendations

A gilt nutritional program should be designed to meet the nutrient demands for adequate protein growth and bone and reproductive tract development. The gilt nutritional program begins at weaning and continues until the end of the first lactation. Designing the nutritional program should focus on avoiding nutrient deficiencies and preventing over conditioning upon entry into the sow herd.

Optimizing growth rate early in the gilts' life has been shown to be beneficial for lifetime productivity. During the preweaned stage, inadequate colostrum consumption after birth can lead to reduced growth rate. A reduction in growth rate during the preweaning stage could lead to delays in puberty attainment and negatively affect reproductive tract development (Vallet et al., 2016). Research has shown that creating smaller litters for gilts destined for the sow population post-farrowing to reduce suckling pressure is beneficial for preweaning growth rate, reproductive performance, and lifetime productivity (Flowers, 2019). Therefore, it is recommended to create smaller litters for gilts destined for the sow population to potentially benefit colostrum intake and lifetime productivity.

During the nursery stage, dietary nutrient recommendations should be similar to commercial pig requirements. This is because a reduction in postweaning gain can lead to decreases in successful mating and reproductive performance (Athorn et al., 2017). During the grow-finish period, ad libitum feeding of a grow-finish diet with moderate levels of energy and amino acids is recommended. This is because increasing the lysine:calorie ratio above normal grow-finish levels shows no evidence for effects on puberty onset or ovulation rate, while severe restriction can lead to delayed puberty (Calderón Díaz et al., 2015). Furthermore, severely restricting energy below growth and maintenance requirements in an effort to slow growth rate during rearing can lead to delays in the expression of estrus (Miller, 2011).

Dietary calcium and phosphorous concentrations fed from 50 to 300 lb should be increased compared to diets fed to commercial finishing pigs to maximize bone mineral content (NRC, 2012). Although this does not necessarily alter growth performance or effect structural soundness, it provides improved bone strength characteristics.

The age and body weight of gilts moved to the breeding herd from the gilt developer facility may affect how diets are formulated. If the replacement gilts are moved to the breeding herd well in advance of typical market weight, then development diets should be fed to match the needs of the growing gilt If replacement gilts are moved to gestation at regular market weight prior to first breeding, they are often switched to gestation diet. This is done in an effort to increase key vitamins such as choline, biotin, pyridoxine and folic acid that are necessary for embryo development. When gilts are moved to gestation before breeding, they are generally limit fed. In this case, approximately 2 weeks prior to breeding, feed intake should be increased by approximately 2 lb per gilt per day to increase energy intake. The increased energy intake can increase the number of eggs ovulated prior to breeding. This practice is commonly referred to as "flushing" (Whitney et al., 2010).

After breeding, feed intake should be adjusted to regular gestation levels to match her body condition. This should be done to avoid rapid weight gain during gestation and preventing over conditioned gilts entering their first lactation. Over conditioned gilts will have decreased lactation feed intake and negative subsequent reproductive performance.

Body Criteria Targets Before 1st Breeding

Target body weight for gilts at breeding should be between 300 to 340 lb to optimize reproductive performance and longevity in the sow herd. This weight threshold is needed at breeding to ensure gilts will not lose excessive protein reserves during their first lactation. Gilts generally have lower lactation feed intake which results in increased mobilization of protein stores for milk production and can lead to decreased reproductive performance (Clowes, 2003). Furthermore, breeding gilts at lighter or heavier weights can decrease total born over their entire lifetime or potentially result in increased stillborn pigs and lameness issues, respectively (Williams et al., 2005). Finally, backfat is not a reliable predictor of subsequent reproductive performance. This is because greater amount of backfat accumulation in gilts shows no evidence for an improvement in reproductive performance (Filha et al., 2010). Accumulating protein reserves is more important as increases in fat accumulation are lost by weaning after the first litter and excess losses in protein reserves can lead to decreased reproductive performance (Gill, 2006).

Therefore, bodyweight should be used as the target criteria before first breeding to optimize reproductive performance. Also, avoiding deficiencies or oversupply of nutrients in the diet helps achieve long-term reproductive success of gilts.

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Gestation

Meeting the nutrient demands of both the gestating sow and developing fetus can be achieved in many different ways. This factsheet will focus on energy, amino acid, and vitamin and mineral considerations for a gestating sow nutritional program.

Energy

Determining Energy Requirement

Energy requirements for gestating sows include maintenance, maternal growth including protein and fat deposition, conceptus (fetus + placenta and fluids + uterus), and mammary tissue (NRC, 2012). Dietary energy for maternal maintenance, conceptus products, and mammary gland development is prioritized and, if excess energy is available, partitioned for maternal gain (NRC, 2012; Figure 1).

The gestating sow basal maintenance requirement (kcal/d) can be expressed as $100 \times BW_{0.75}$ where BW is body weight in kg (NRC, 2012). Thus, with increasing bodyweight, maintenance energy requirements increase. Environmental conditions such as temperature influence maintenance energy requirements (NRC, 2012). Because gestating sows are restrictively fed to control weight gain, body heat production is low. However, at temperatures below 68°F, for every 1° decrease in temperature, feed allowances should be increased by 0.05 lb.

Setting Feed Allowances

Feed allowances must be adjusted based on BW to meet maternal maintenance and conceptus energy requirements. Once those requirements are met, any extra energy will be directed towards gain. Gilts require less energy for maintenance and more for gain as they have not yet reached mature body weight. Older parity sows' maintenance requirement increases with increasing bodyweight, but less energy is required for gain (Figures 2 and 3). To establish the proper feed allowance for gestating sows, an objective measure should be used to maintain sows in proper body condition. Sows should be identified as thin, ideal, or over conditioned. Feed allowance should then be adjusted accordingly. Variation in feed drop accuracy can occur based on different types of feed drops, bulk density of the diet and how they are mounted on feed lines (Schneider et al., 2008). Thus, the feeding system should be calibrated for accurate daily feed delivery.

Energy Requirements in Late Gestation

Fetal development changes dramatically during the gestation period. In early to mid-gestation, energy is primarily used for maternal maintenance and protein deposition. At approximately d 70 of gestation, energy retention is shifted more towards the growing demands for conceptus development (McPherson et al., 2004). Mammary development accelerates at approximately d 80 of gestation further shifting energy retention away from maternal growth (Kim et al., 2013). Feeding additional energy and amino acids through increasing feed allowances has been a common practice to meet the shifting late term gestating sow energy demands in an attempt to increase birth weight. While research data indicates increasing feed allowances will increase sow weight gain and backfat depth, the impact on birth weight is modest with negative impacts on lactation feed intake and stillbirth rate. Therefore, providing extra feed during late gestation does not appear to be necessary and in many instances not economically justified.

Fiber

Restricting feed intake can potentially lead to aggressive behaviors due to unfulfilled feeding motivation and satiety (Meunier-Salaün et al., 2001). Feeding dietary fiber can increase satiety and reduce aggressive behaviors, but the influence on reproductive performance is inconclusive at this time (McGlone and Fullwood, 2001; Holt et al., 2006). However, providing fiber in a restricted-fed gestation diet shows no evidence for negative effects on reproductive performance (Wilson et al., 2003; Holt et al., 2006; Guillemet et al., 2007).

When feeding fiber in gestating sow diets, some considerations exist. First, the energy value of the fibrous ingredient should be accurately estimated. The net energy and bulk density of most fibrous ingredients is lower than corn. Because fibrous ingredients lower the energy density and increase the bulkiness, feed allowances must be increased. The increase in feed allowance potentially could offset a lower diet cost. Volumetric feed delivery should be adjusted as diet bulk density can affect the amount of feed being delivered. Finally, pelleting diets can negate dietary fiber benefits on satiety during restricted feed intake as it can improve the digestibility of nutrients (De Vries et al., 2012).

The economic value of higher fiber ingredients is generally greater in gestation diets as it can potentially lower diet costs and has no evidence for a negative impact on reproductive performance.

Amino Acids

Determining AA Requirements

Time- and energy-dependent maternal protein deposition for weight gain are the tissue pools that require the greatest amount of amino acids (Figure 4). Time-dependent protein deposition for maternal gain is greatest in the early part of gestation and this best represents the time that body protein reserves can be replenished from losses during lactation. Energy-dependent maternal protein deposition represents the relationship between energy intake and protein deposition. This type of maternal protein deposition can vary with parity as gilts will deposit more protein with increased energy intake as they have yet to reach mature body weight. This relationship will essentially be 0 in parity 4+ sows (Dourmad, 2008). Furthermore, fetal and mammary tissue growth are the next greatest need for amino acids. Amino acid requirements for these tissues begin to increase from d 60 until the end of gestation.

AA Requirements

Daily amino acid requirements can be calculated from these determinants and should be expressed on a g/d basis. From the desired feed allowances in gestation, amino acid levels can be set in diet formulation to meet the g/day requirement.

Limited research has focused on gestating sow amino acid nutrition. From this limited research, lysine has been the most extensively evaluated amino acid. The lysine requirement of gestating sows changes based on parity and stage of gestation. Gilts and younger parity sows will have greater lysine needs to support maternal gain to achieve mature weight but this requirement decreases with older parity sows (Samuel et al., 2012). Furthermore, the lysine requirement increases from early to late gestation and this change is due to the demands required for fetal growth and mammary development. Providing increased dietary lysine in late gestation has the potential to positively influence sow performance and pig birth weight. From this data, it is recommended that gestating gilts and sows receive 11 to 13 g/d of SID lysine (Goncalves et al., 2016; Thomas et al., 2018).

After lysine levels are set, other amino acids relative to lysine can be calculated. Compared to lysine, limited research exists on other amino acid requirements and these recommendations are mostly based on modeling of amino acid use (Leveseque et al., 2011; Franco et al., 2014).

Because research has shown that amino acid requirements increase in late gestation, the concepts of phase-feeding and parity-segregated feeding have been proposed (Moehn and Ball, 2013). These concepts require the blending of 2 diets or increased movement of animals within the gestation barn to segregate by parity. Due to facility and logistical constraints, this can be difficult to implement. Therefore, most production systems will provide a single diet throughout gestation. (Table 1).

Vitamins and Minerals

Ca and P

The phosphorous requirement for gestating sows is determined by requirements for maternal maintenance to replace minimum urinary and basal endogenous losses, maternal phosphorous retention for growth, and development of the conceptus and mammary glands (Bikker and Blok, 2017). Similar to energy and amino acids, the phosphorous requirement for gestating sows increase in late gestation to meet the demands for conceptus development and growth (Mahan et al., 2009). Parity can also dictate the phosphorous requirement as gilts and younger parity sows will require greater amounts of phosphorous on a daily basis to support growth as they have not yet reached mature bodyweight. Older parity sows will require less phosphorous to maintain bodyweight and body reserves. Calcium requirements increase in a similar manner as phosphorous in late gestation to support fetal development (Mahan et al., 2009). The relationship between calcium and phosphorous must be considered as both minerals are essential for development of the skeletal system, but excessive dietary Ca can inhibit P retention and absorption in the body (Létourneau-Montminy et al., 2012). Limited data exists on the calcium and phosphorous requirements for gestating sows. Research has shown that low calcium and phosphorous intake can result in lameness, while providing increased amounts of calcium and phosphorous has no effect on reproductive performance or structural soundness (Giesemann et al., 1998; Tan et al., 2016). It is recommended that gestating gilts and sows be provided 11.3 g/d of STTD phosphorous and 14.3 g/d of STTD calcium. These recommendations are above NRC (2012) levels to provide a margin of safety (Table 2). Furthermore, the use of phytase in gestating sow diets can improve the digestibility and retention of calcium and phosphorus (Lee et al., 2018). Therefore, phytase is recommended for use in gestating sow diets. Calcium and phosphorous release values should be applied in diet formulation when using phytase.

Trace Minerals

Because of variability in concentrations as well as bio-availability, copper, zinc, iron, iodine, manganese, chromium, and selenium are typically supplemented to gestation and lactation diets (link to GN trace mineral premix). Increased supplementation above these recommended levels and effect on reproductive performance is inconclusive and not recommended (Chen et al., 2016; Van Riet et al., 2018). Furthermore, organic sources of trace minerals in gestating sows have been researched, but results are inconclusive versus inorganic sources (Peters and Mahan, 2008; Bradley, 2010; Novais et al., 2016).

Vitamins

A standard practice is to provide additional vitamins that are not included in growing pig diets which include biotin, folic acid, pyridoxine and choline. Also carnitine, a vitamin like compound, is often included (link to Vitamin premix). In the KSU sow add pack, vitamin A and E are also provided to achieve higher levels than required by growing pigs. Providing these extra vitamins can be achieved by using a sow add pack or separate vitamin premix designed for sows only.

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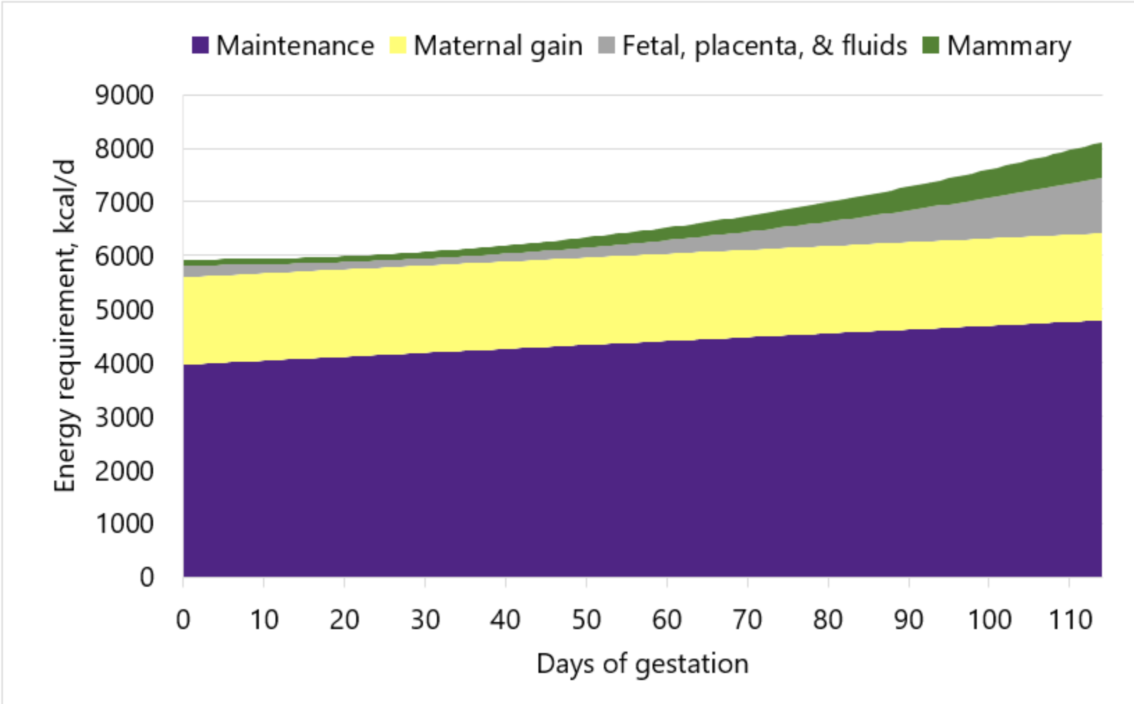

Figure 1. Energy needs of gilts during gestation based different body tissues (Adapted from NRC, 2012).

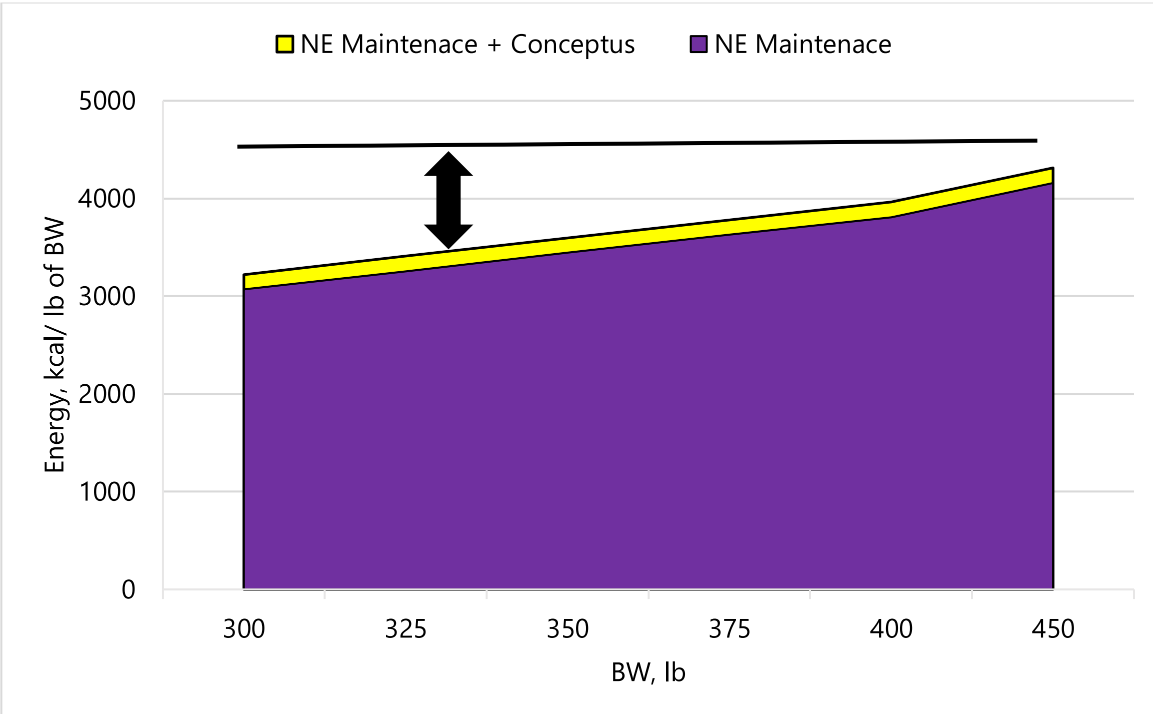

Figure 2. Estimated maintenance and maintenance plus conceptus energy (NE) requirements for gilts based on BW. Bold line indicates energy provided from a 4 lb feed allowance of a corn-soybean meal diet containing 1,123 kcal of NE/lb. Arrow indicates energy remaining that is available for maternal gain.

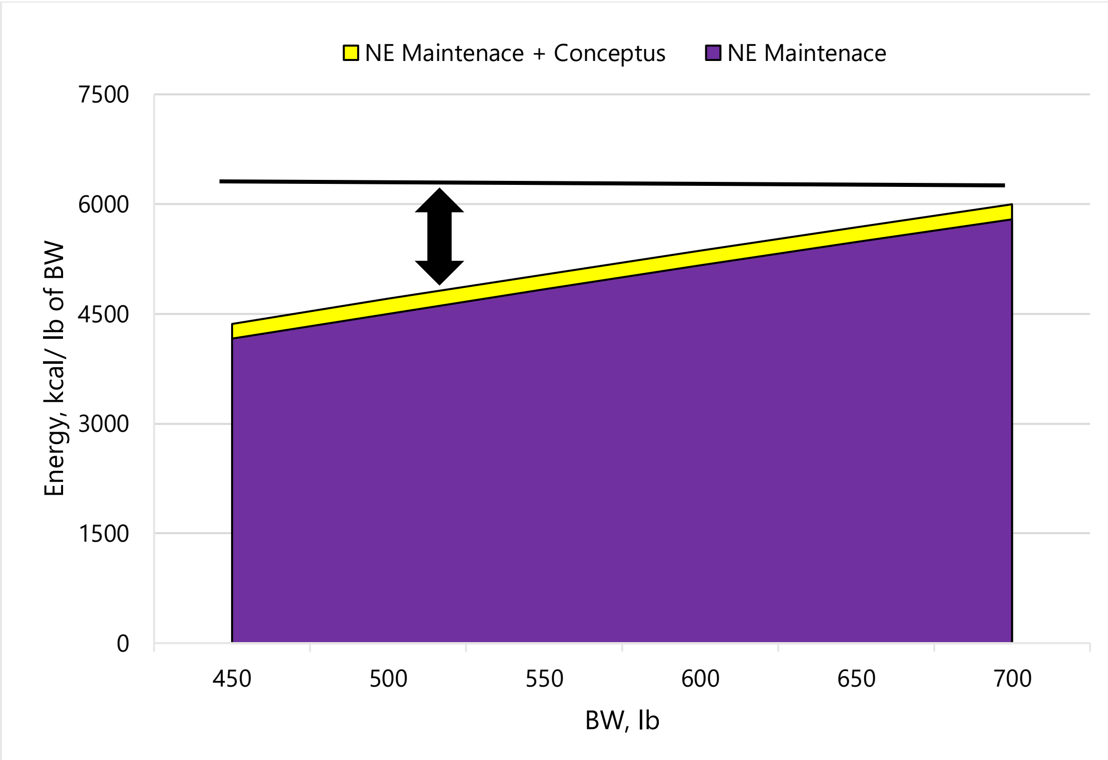

Figure 3. Estimated maintenance and maintenance plus conceptus energy (NE) requirements for parity 1+ sows based on BW. Bold line indicates energy provided from a 5.5 lb feed allowance of a corn-soybean meal diet containing 1,123 kcal of NE/lb. Arrow indicates energy remaining that is available for maternal gain.

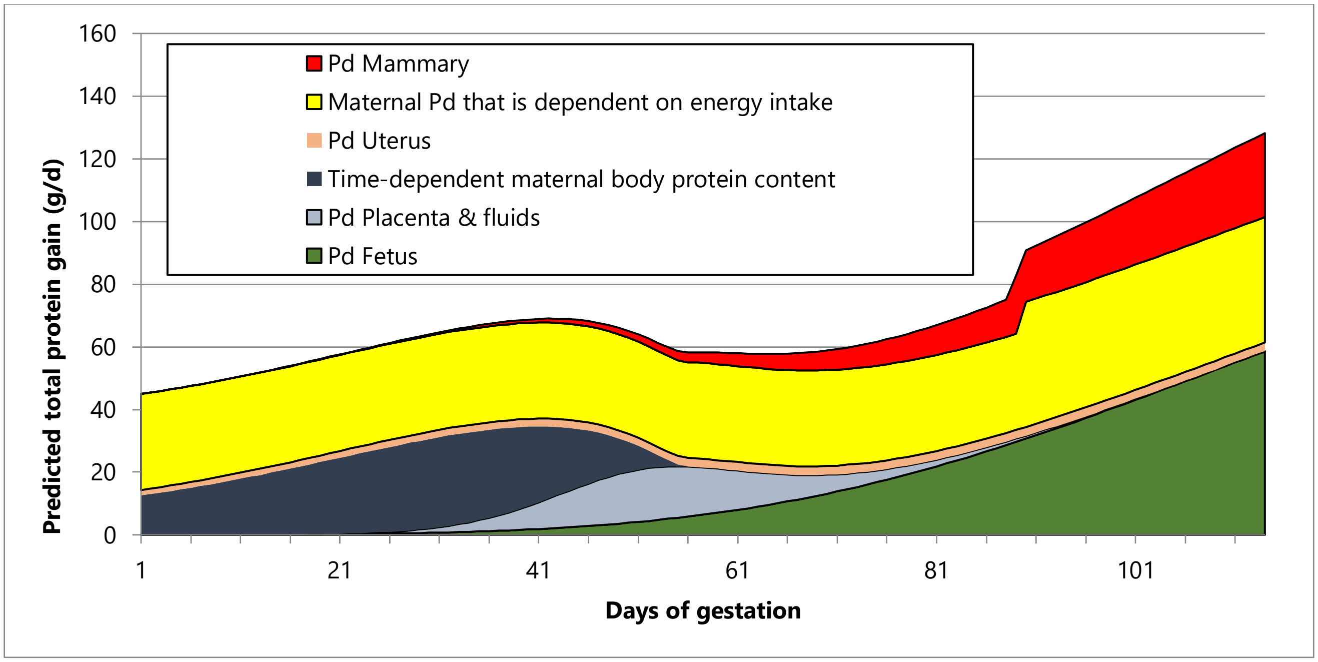

Figure 4. Predicted total protein gain (Pd: g/d) of second parity sows during gestation (Adapted from NRC, 2012).

Table 1. Dietary recommendations for gestating sows

SID amino acids[1]	
Lysine, %[2]	0.60
SID amino acid to lysine ratio, %[3]	
Methionine	28-29
Methionine + Cysteine	68-70
Threonine	74-76
Tryptophan	19-21
Isoleucine	58
Valine	71-76
Total calcium, %[4]	0.80
Available phosphorous, %	0.48
STTD phosphorus , %	0.50
STTD calcium, %	0.59
Ca:STTD P	1.60
STTD Ca:STTD P	1.26
Vitamins[5]	
Vit A, IU/ton	10,000,000
Vit D, IU/ton	1,500,000
Vit E, IU/ton	60,000
Vit K (menadione), mg/ton	3,000
Vit B12, mg/ton	30
Niacin, mg/ton	45,000
Pantothenic Acid, mg/ton	25,000
Riboflavin, mg/ton	7,500
Biotin, mg/ton	200
Folic acid, mg/ton	2,000
Pyridoxine, mg/ton	900
Choline, mg/ton	500,000
Carnitine, mg/ton	45,000
Trace Minerals[5]	
Zinc, ppm	110
Iron, ppm	110
Manganese, ppm	33
Copper, ppm	17
Iodine, ppm	0.30
Selenium, ppm	0.30
Chromium, ppb	198

[1]Minimum levels based on NRC (2012) ingredient loading values; SID = Standardized ileal digestible.
[2]Minimum lysine level in a diet with 1,123 kcal NE/lb. Lysine level based on 5 lb feed allowance to provide 13.6 g of lys/d.
[3]Data on amino acid requirements for contemporary sows is limited.

[4] Ca and P recommendations for gestating sows based on a 1,123 kcal of NE/lb diet.
[5] Added levels based on KSU vitamin, sow add pack, and trace mineral premixes.

Pre-Farrow Feeding

The transition period between the end of gestation housing to parturition in a farrowing room is a short time period. However, the method of how a sow is fed in this time frame can affect lactation feed intake, colostrum synthesis, sow weight loss, and litter performance.

In most commercial production systems, gestating sows are moved to the farrowing house between approximately day 112 and 114 of gestation. During the short time period prior to farrowing, nutrient requirements are dynamically shifting to support maternal maintenance as well as colostrum synthesis and conceptus development. Maternal maintenance represents the greatest proportion of the energy requirements needed prior to parturition, but the energy requirement for colostrum production and fetal development is continually increasing. It is estimated that energy requirements increase approximately 60% in late gestation prior to parturition (Feyera and Thiel, 2017; Figure 1a). Also, it is estimated that the SID lysine requirement increases to approximately 35 g/day in the last few days prior to farrowing (Feyera and Thiel, 2017; Figure 1b). The increase in lysine requirement is due to the rapid development of the conceptus and colostrum production. Restriction of feed intake during the prepartum period can lead to increased backfat loss and reduced colostrum yield in sows (Decaluwé et al., 2014). Providing ad libitum feed upon entry into the farrowing facility promotes feed intake during farrowing and reduces mobilization of body reserves to maintain body condition throughout lactation (Cools et al., 2014). In addition, recent data suggests that farrowing duration, farrowing assistance, and stillbirth rate were all reduced the closer the last meal was consumed before parturition (Feyera et al., 2018). Although energy and amino acid requirements are increasing, providing ad libitum intake of the lactation diet pre-farrowing can easily meet these requirements.

Using a specific transition diet, different than gestation or lactation diets is a concept promoted in Europe. A transition diet in late gestation is a concept that has been developed to support these increasing nutrient demands as sows approach parturition and early lactation. However, evidence is inconclusive on the benefits of specific transition diets, but providing the lactation diet prior to parturition can improve colostrum quality and intake (Garrison et al., 2017). Therefore, sows should be provided the lactation diet ad libitum upon entry into the farrowing house around day 112 to 114 of gestation to meet increased energy and nutrient needs.

Before implementing ad libitum feeding when moving sows into the farrowing house, farms need to examine how many days before farrowing sows are provided feed ad libitum. If done for an extended period of time, ad libitum feeding prior to farrowing could lead to over conditioned sows which will result in decreased lactation feed intake and increased stillbirth rate (Lavery et al., 2019). Therefore, sows should only be allowed ad libitum feed intake for no more than 3 to 4 days prior to farrowing. To achieve this, producers should have an understanding of the average day of gestation their sows farrow to implement ad libitum feeding properly. In summary, providing the lactation diet ad libitum for no more than 3 to 4 days before farrowing will promote feed intake, improve colostrum quality, and maintain body condition throughout lactation.

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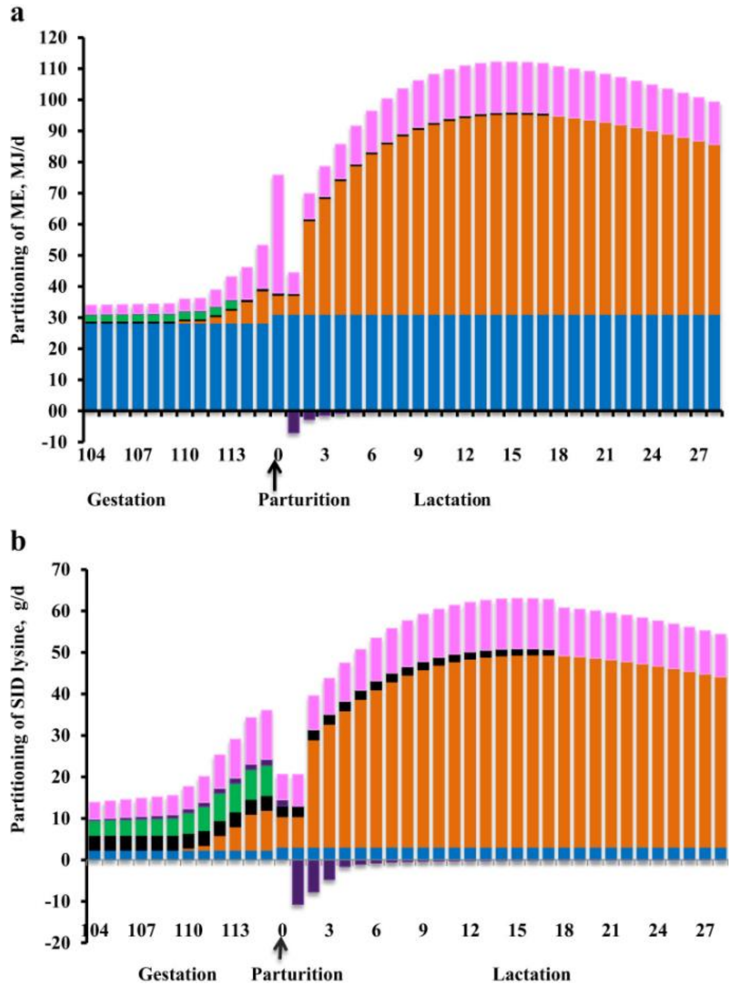

Figure 1. Calculated metabolizable energy (panel a) and lysine (panel b) requirements for maintenance (blue bars), colostrum/milk production (orange bars), mammary growth (black bars), fetal growth (green bars), uterine components (purple bars) and additional heat loss for energy or oxidation/transamination or amino acids (pink bars) in sows during transition and lactation (Reprinted from Livestock Science, 201, Feyera and Theil, Energy and lysine requirements and balances of sows during transition and lactation: A factorial approach, 50-57, 2017, with permission from Elsevier).

Lactation

Milk production requires the greatest proportion of nutrients during lactation. Thus, maximizing feed intake and adequate dietary amino acids will prevent sow body reserve mobilization and sustain milk production for litter growth. This factsheet will discuss energy, amino acid, and vitamin and mineral recommendations for the lactating sow.

Energy

Genetic selection has dramatically increased litter size and milk production in sows. This has resulted in increased body energy demands. Furthermore, the modern prolific sow is characterized with having less body fat reserves, which are necessary to buffer energy needs not met by feed intake (Lewis and Bunter, 2011). When feed intake is lower than body energy demand, the sow will mobilize body stores from fat and muscle to sustain milk production. Restricted feeding, intentionally or unintentionally, will result in greater sow body tissue mobilization which causes excessive weight loss, less milk production, and reduced litter growth rate (De Bettio et al., 2016). Implementation of ad libitum feeding systems in farrowing houses have enhanced lactation feed intake and many producers in the US have adopted this technology.

Determining Energy Requirement

Maternal maintenance and milk production are the determining factors for the energy requirements of lactating sows. Similar to gestating sows, maintenance requirements can be expressed as $100 \times BW_{0.75}$ with bodyweight in kg (NRC, 2012). Maintenance energy requirements represent a relatively small contribution to the total energy requirement for lactating sows. This is because milk production represents 65 to 80% of the total energy requirement (Figure 1). The NE requirements for maintenance of lactating sows stays constant over lactation. Milk production, however, increases threefold within the first week of farrowing and demands are dictated by litter size and litter growth rate. Thus, large litter sizes and high litter growth rates will increase the energy requirement for milk production. Net energy intake for sows will increase as lactation progresses, but often will not meet the combined energy requirement for maintenance and milk production. Sows will mobilize body reserves to meet requirements (Table 1; Pedersen et al., 2019). The negative energy balance results in weight loss and excessive weight loss during lactation can lead to negative effects on subsequent reproductive performance (Thaker and Bilkei, 2005). Finally, gilts will have approximately 15% lower daily feed intake compared to older parity sows (Strathe et al., 2017). Therefore, maximizing gilt lactation feed intake is critical.

Energy Level and Source

Energy concentration in lactation diets will have an effect on total feed intake (Strathe et al, 2017). Increasing the energy concentration of the diet can increase energy intake, reduce weight loss, and increase litter growth rate at the same feed intake (Xue et al., 2012). However, a dietary energy concentration level is reached at which feed intake can be negatively affected (Xue et al., 2012). To achieve greater energy density in the diet, fats and oils are commonly used as they are a highly digestible energy source for sows. The additional energy from dietary fat is partitioned for milk and converted as milk fat output (Rosero et al., 2015). Addition of fats and oils to the diet have been shown to improve energy intake, milk fat output and improve litter growth rate (Rosero et al., 2016).

Dietary fat source quality should be considered. Addition of fats with high free fatty acids and peroxide profiles could be less digestible and more susceptible to oxidation. Furthermore, addition of high fiber ingredients lowers the energy density and increases the bulk density of the diet. However, feeding moderate levels of fiber in lactation is a strategy that can be employed in an effort to decrease feed costs.

In summary, if high quality fat is available, it is often recommended that corn-soybean meal lactation diets with 2 to 4% added fat be formulated to provide between approximately 1,120 and 1,200 kcal NE/lb to increase energy intake without adversely affecting feed intake.

Essential Fatty Acids

Linoleic and α-linolenic acid are classified as nutritionally essential fatty acids (EFA) because they cannot be synthesized by mammals. They can serve as precursors for other important polyunsaturated fatty acids (PUFAs) such as eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA), and arachidonic acid (ARA) (Bontempo and Jiang, 2015). Linoleic and α-linolenic acid can be found in grain and vegetable oils, such as soybean and corn oil, while EPA and DHA are mainly found in fish oils. Addition of EFAs to lactating sow diets has shown improvements in litter performance and subsequent sow reproductive performance and played a role in stimulating an immune response in piglets (Farmer et al. 2010; Rosero et al., 2016). Therefore, the amount of essential fatty acids in the diet is important as sows will secrete EFAs in the milk. Research is still limited on the minimal total EFA provided from ingredients that improves lactation and subsequent reproductive performance. Rosero et al. (2016) recommends that sows consume 125 g/d of linoleic and 10 g/d of linolenic fat during lactation. Ingredients containing high levels of these EFAs (flax seed oil, corn oil, soybean oil and menhaden oil) can substantially increase diet costs. Therefore, nutritionists need to balance the cost of meeting minimal EFA levels with the potential benefits in reproductive performance.

Amino Acids

Milk protein synthesis constitutes approximately 70% of lactating sow amino acid requirements (Pedersen et al, 2019). Therefore, the number of pigs nursing in the litter and the litter growth rate will dictate the amino acid requirements of lactating sows (Table 2). It has been established that a balanced supply of amino acids close to the requirements is needed as this improves milk protein output and litter performance as well as reduces protein mobilization from tissues (Gourley et al., 2017; Strathe et al., 2017; Pederson et al., 2019).

Amino Acid Requirements

Lysine is the first limiting amino acid in most diets and lactating sows with larger and faster growing litters will require greater amounts of daily lysine to meet their needs. Previous research demonstrated that excessive weight loss and mobilization of body reserves during lactation impaired subsequent reproductive performance (Thaker and Bilkei, 2005). (Xue et al., 2012; Shi et al., 2015; Gourley et al., 2017). However, recent studies have shown inconclusive results on the influence of lysine intake on subsequent reproductive performance (Shi et al., 2015; Gourley et al., 2017). The equivocal results with reducing body reserve mobilization by increasing lysine intake could be due to the modern lactating sow having more protein reserves and being more resilient to the negative effects of body reserve mobilization from reduced feed intake (Patterson et al., 2011).

A sow lactation research summary using published data from 1972 to 1997 determined that approximately 11 g/ SID lysine intake per day was needed for each 1 lb increase in litter growth rate (Boyd et al., 2000). A more recent review has updated this regression analysis to include sows from 1998 to 2017 and determined that approximately 60 g/ SID lysine intake per day is needed to optimize litter growth rate for most sows (Figure 2; Tokach et al., 2019).

There is limited research directly measuring milk production or litter responses to other amino acids as compared to lysine (Fan et al., 2016; Greiner et al., 2017; Xu et al., 2017). After lysine levels are set, other amino acids relative to lysine can be calculated using the amino acid profile in milk and mammary tissue as well as the dynamic nature of body tissue mobilization during lactation (Kim et al., 2001). Amino acid recommendations for lactating sows are provided (Table 3).

Protein and Amino Acid Sources

The increased availability of feed-grade amino acids has allowed producers to reduce diet costs by including feed-grade amino acids to replace soybean meal in the diet while meeting amino acid requirements. Additionally, including more than 30% soybean meal in the diet can lead to reductions in feed intake (Gourley et al., 2019). Conversely, some research has observed decreases in litter growth rate based on parity and increases in preweaning mortality with increasing amounts of feed-grade amino acids in the diet (Touchette et al., 1998; Greiner et al., 2018). Current research indicates that lactation diets should be formulated with a minimum dietary digestible protein of 14% (approximately 16% crude protein; Strathe et al., 2017).

Vitamins and Minerals

Ca and P

The Ca and P requirements for lactating sows are largely determined by milk production and output of Ca and P in the milk (Bikker and Blok, 2017). With larger litter sizes and faster litter growth rates, calcium and phosphorus requirements will increase considerably throughout lactation to support the demand in milk production (Table 4). Gilts and younger parity sows will have greater needs to support maternal growth and development as they have not yet reached mature size (NRC, 2012). Also, gilts and younger parity sows may require greater Ca and P requirements as they potentially could have smaller mineral reserves for body mobilization compared to older parity sows (NRC, 2012). Limited data exists on Ca and P requirements for lactating sows and the mobilization of body reserves makes these requirements more difficult to estimate (Table 5).

Vitamins and Trace Minerals

Similar to gestating sows, trace mineral and additional vitamin supplementation is provided through a premix and a sow add pack or a vitamin premix designed for sows only.

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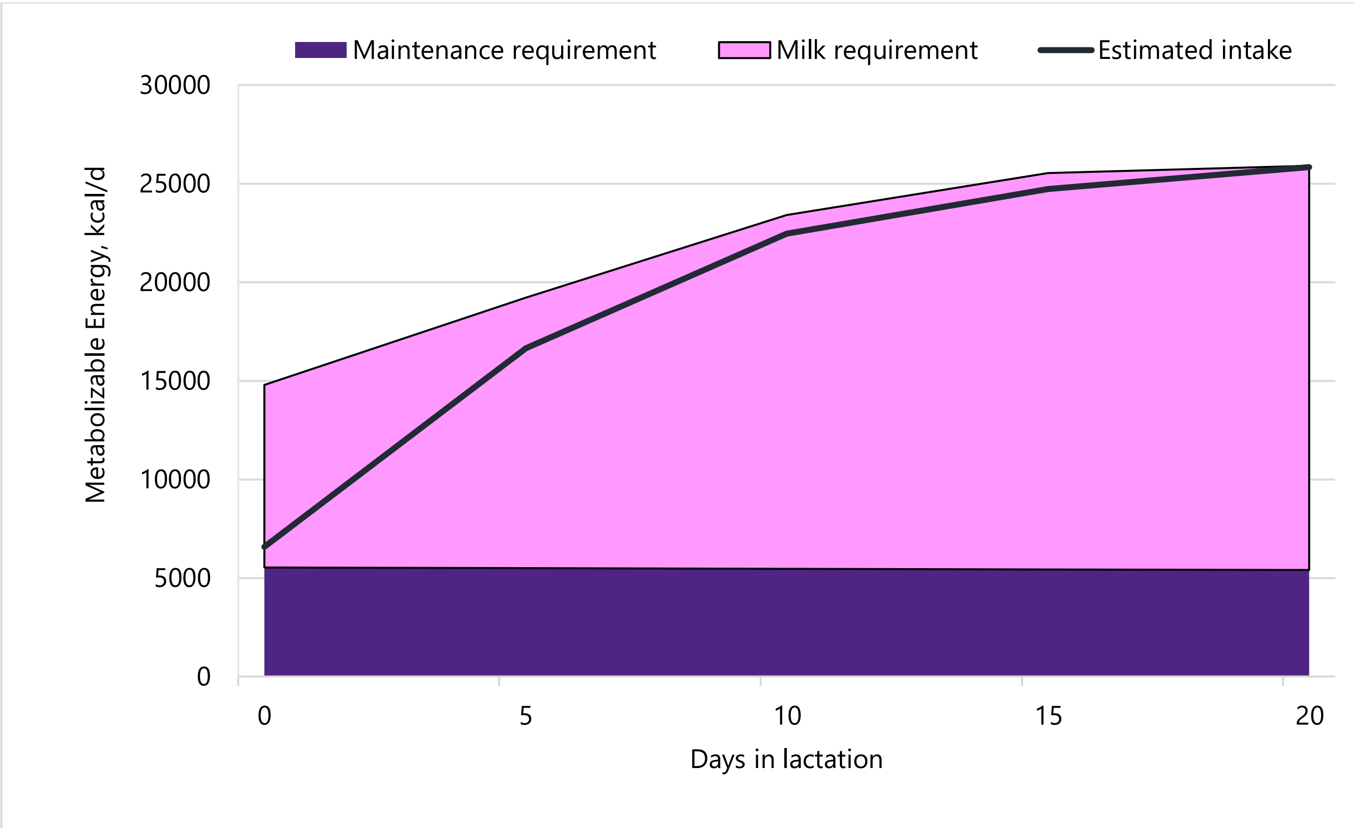

Figure 1. Estimated metabolizable energy (ME) requirements for maintenance and milk production and expected energy intake of lactating sows. Estimates were derived from the NRC (2012) assuming a litter size of 11.5 piglets and litter gain of 5.9 lb/d in a 21-d lactation period for multiparous sows.

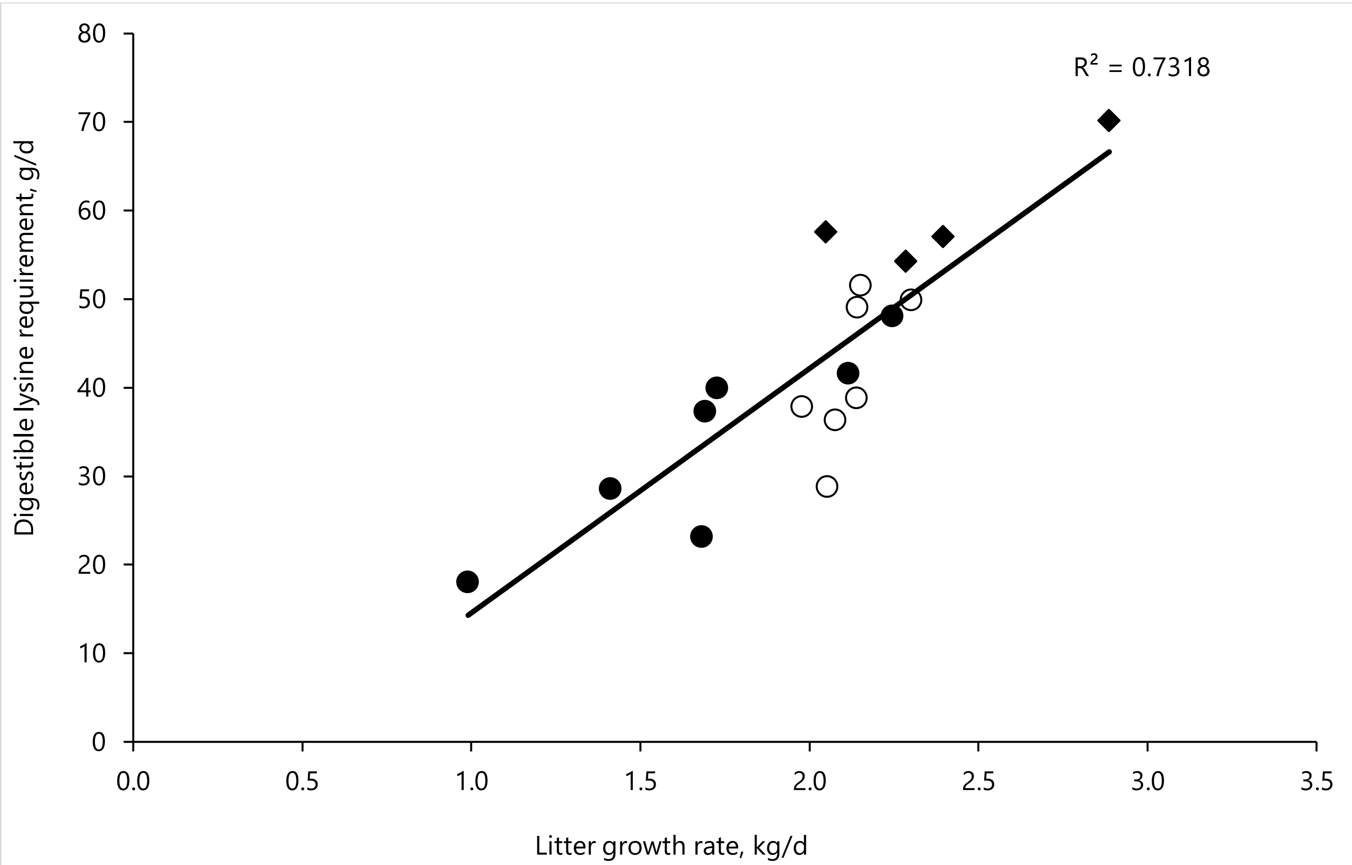

Figure 2. Relationship between dietary lysine intake and litter growth rate (Tokach et al., 2019).

Table 1. Daily milk production and mobilization of body reserves of lactating sows based on litter size and weaning weight[1]

Piglets per litter, n:	10	12	14	16
Piglet weaning weight, lb:	16	15	14	13
Milk production, lb/d	19	23	25	26
Sow body weight gain, lb/d	-0.45	-1.40	-2.02	-2.13
Sow body protein deposition, lb/d	-0.05	-0.14	-0.20	-0.21
Sow body fat deposition, lb/d	-0.23	-0.70	-1.00	-1.06

[1]Estimates derived from the NRC (2012) model assuming a feeding level of 14 lb/d of a lactation diet containing 1,122 kcal NE/lb in a 21-d lactation for multiparous sows.

Table 2. Daily SID lysine requirement (g/day) estimates of lactating sows based on litter size and weaning weight

	Piglets per litter, n			
Piglet weaning weight, lb	10	12	14	16
13	44	48	53	58
14	45	50	55	61
15	47	52	58	63

[1]Estimates derived from the NRC (2012) model assuming a feeding level of 14 lb/d of a lactation diet containing 1,122 kcal NE/lb in a 21-d lactation for multiparous sows. For primiparous sows, the lysine requirements in grams per day are approximately 5% lower due to lower milk production but approximately 5% higher as a diet percentage due to lower feed intake.

Table 3. Suggested minimum standardized ileal digestible lysine and amino acid to lysine ratios for lactating sows

SID amino acids[1]	
Lysine, %[2]	1.05

Amino acid to lysine ratio, %[3]	
Methionine	28-29
Methionine + Cysteine	53-54
Threonine	63-64
Tryptophan	19-21
Isoleucine	56
Valine	64-70

[1]Minimum levels based on the NRC (2012) ingredient loading values.
[2]Minimum lysine levels assuming a feeding level of 14 lb/d of a lactation diet containing 1,122 kcal NE/lb in a 21-d lactation for primiparous sows weaning 14 pigs.
[3]Data on amino acid requirements for contemporary sows is limited.

Table 4. Daily phosphorous estimates (g of STTD P/d) of lactating sows based on litter size and weaning weight[1]

	Piglets per litter, n			
Piglet weaning weight, lb	10	12	14	16
13	44	48	53	58
14	45	50	55	61
15	47	52	58	63

[1]Estimates derived from the NRC (2012) model assuming a feeding level of 14 lb/d of a lactation diet containing 1,122 kcal NE/lb in a 21-d lactation for multiparous sows. For primiparous sows, the phosphorus requirements in grams per day are approximately 5% higher as a diet percentage due to lower feed intake. Total calcium intake is estimated at 2x of the digestible phosphorus requirement.

Table 5. Vitamin and mineral recommendations for lactating sows[1]	
Total calcium, %	0.80
Available phosphorous, %	0.45
STTD phosphorus , %	0.50
STTD calcium, %	0.59
Ca:STTD P	1.60
STTD Ca:STTD P	1.18
Vitamins[2]	
Vit A, IU/ton	7,500,000
Vit D, IU/ton	1,500,000
Vit E, IU/ton	60,000
Vit K (menadione), mg/ton	3,000
Vit B12, mg/ton	30
Niacin, mg/ton	45,000
Pantothenic Acid, mg/ton	25,000
Riboflavin, mg/ton	7,500
Biotin, mg/ton	200
Folic acid, mg/ton	2,000
Pyridoxine, mg/ton	900
Choline, mg/ton	500,000
Carnitine, mg/ton	45,000
Trace Minerals[2]	
Zinc, ppm	110
Iron, ppm	110
Manganese, ppm	33
Copper, ppm	17
Iodine, ppm	0.30
Selenium, ppm	0.30
Chromium, ppb	198

[1]Ca and P recommendations for lactating sows based on a 1,120 kcal of NE/lb diet.
[2]Added levels based on KSU vitamin, sow add pack, and trace mineral premixes.

Wean-to-Estrus

The average wean-to-estrus interval (WEI) on commercial farms is approximately 5 days with most sows bred within 7 days of weaning (Knox et al., 2013). Due to the energy and amino acid demands during lactation, many sows and gilts will have lost weight (body condition) during lactation. Large losses in body condition can potentially lead to a prolonged WEI in parity 1 and 2 females (Vargas et al., 2009). Although limited research exists on feeding strategies during the WEI, recent research has found little to no impact of increasing feed intake of a gestation diet or feeding a lactation diet between weaning and rebreeding (Graham et al., 2015; Almeida et al., 2018; Tables 1 and 2). Therefore, when transitioning into the WEI, it is recommended that weaned sows be provided 6 to 8 lb/d of the gestation diet to restore body reserves, then transition to gestation feed allowances based on body condition (Figures 1 and 2).

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Table 1. Effects of wean-to-estrus feeding level on post-weaned sow performance[1]

	Feeding Level (lb/d)		
Item	6	8	12
ADFI, lb[2]	5.9	7.8	11.4
Wean-to-Estrus interval, d	5.1	5.0	4.9
Conception rate, %	95.6	95.6	94.7
Subsequent total born, pigs/sow	14.3	13.9	13.9

[1]Adapted from Graham et al. (2015)
[2]Values differed significantly (*P* < 0.01)

Table 2. Effects of feeding level and diet type on post-weaned sow performance[1]

Diet Type:	Gestation		Lactation	
Feeding Level:	6	8	6	8
Wean-to-estrus interval[2]	4.3	4.1	4.1	4.3
Total born, n	15.0	15.4	15.1	15.1
Born alive, %[3,4]	92.2	91.7	91.7	89.9
Litter born alive weight, lb[5]	37.7	39.5	39.0	37.9
Individual born alive weight, lb	2.73	2.87	2.87	2.84

[1]Adapted from Almeida et al. (2018)
[2]Feed type × Feed amount (*P* = 0.021)
[3]Feed type (*P* = 0.080)
[4]Feed amount (*P* = 0.070)
[5]Feed type × Feed amount (*P* = 0.084)

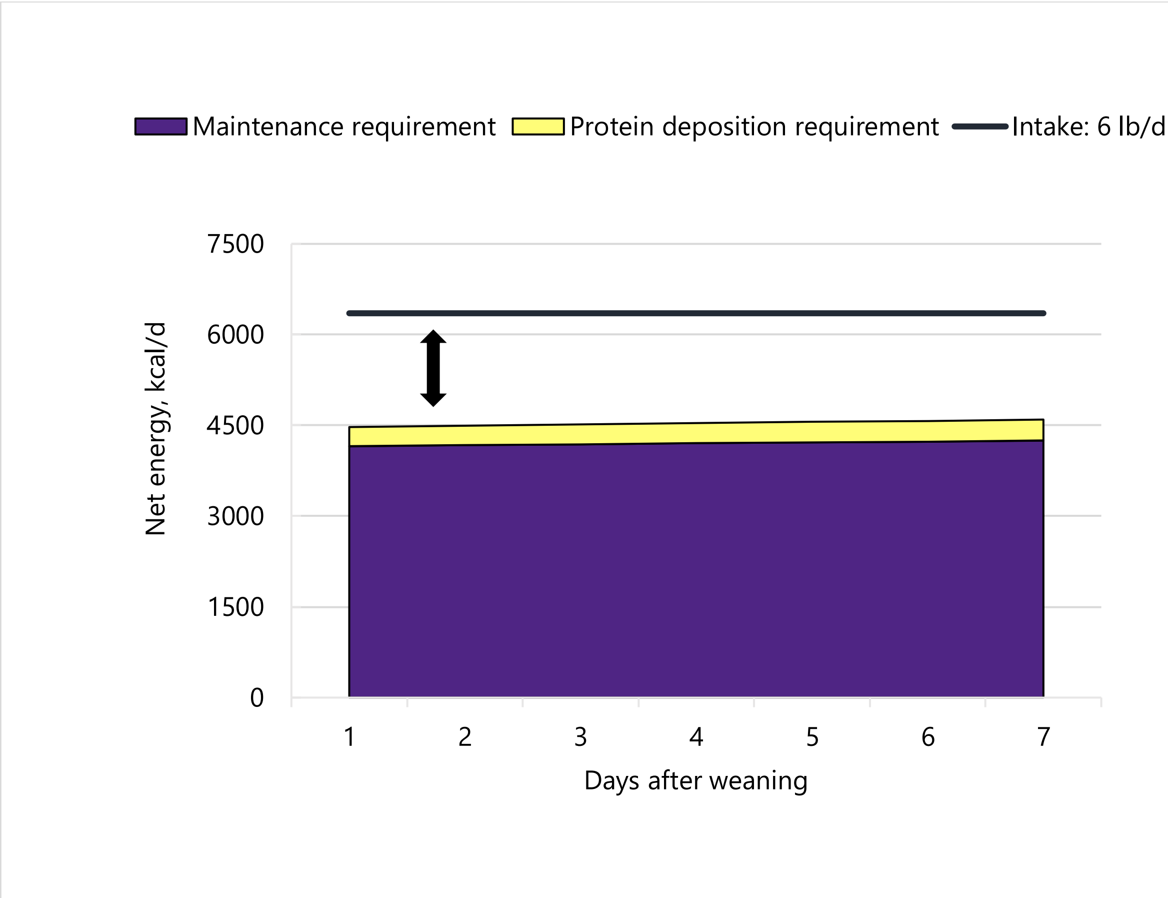

Figure 1. Estimated daily maintenance energy (NE) requirements and feed intake in the wean-to-estrus interval (Adapted from NRC, 2012). Arrow indicates energy left over for recovery of body reserves.

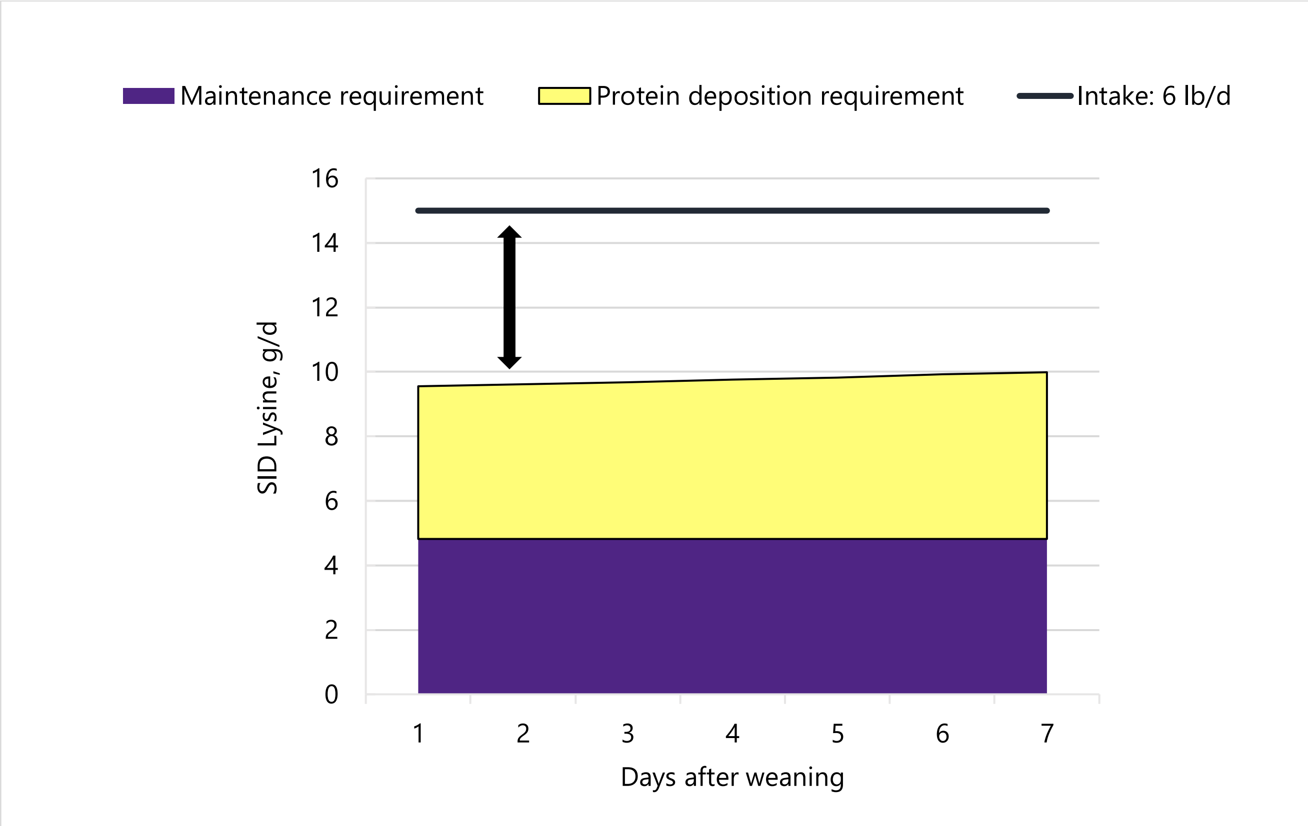

Figure 2. Estimated daily standardized ileal digestible (SID) lysine requirement and feed intake in the wean to estrus interval (Adapted from NRC, 2012). Arrow indicates energy left over for recovery of body reserves.