THE EFFECTS OF STANDARDIZED ILEAL DIGESTIBLE TRYPTOPHAN:LYSINE RATIO IN NURSERY AND FINISHING PIGS; AND REGRESSION ANALYSIS TO PREDICT GROWTH PERFORMANCE FROM DIETARY NET ENERGY

by

SUREEMAS NITIKANCHANA

D.V.M., Chulalongkorn University, 2010

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Diagnostic Medicine/Pathobiology
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Abstract

A total of 8 experiments and a meta-analysis were performed with the overarching goal to improve amino acid and energy utilization in swine diets. The first experiment used a total of 255 nursery pigs to evaluate the optimum dietary standardized ileal digestible (SID) tryptophan to lysine (Trp:Lys) ratio. Four experiments also were conducted using 6,668 finishing pigs to determine the effects of SID Trp:Lys ratio in diets containing dried distillers grains with solubles (DDGS) on growth performance and carcass characteristics. A subsequent experiment evaluated the interaction between Trp and large neutral amino acids (Trp:LNAA) on growth performance of early and late-finishing pigs. Lastly, data from 41 trials and 2 validation trials were used to develop a regression equations to predict ADG or gain to feed (G:F) as influenced by BW and net energy (NE) content in growing-finishing pigs. In Exp. 1, the growth performance and economics indicated the optimum SID Trp concentration for 6-to 10-kg nursery pigs at 20.3% of Lys. In Exp. 2, 3, and 4, there were no differences in growth performance due to SID Trp:Lys ratio; however, increasing the SID Trp:Lys ratio suggested an opportunity to improve carcass yield and lean in pigs fed high levels of DDGS. Experiment 5 indicated an optimum SID Trp:Lys ratio of 20% for 71- to 127-kg pigs fed high level of DDGS. In Exp. 6, growth performance was unaffected by dietary treatment suggesting that 16.5% SID Trp:Lys was adequate to prevent a negative impact on growth when SID Trp:LNAA was as low as 3.0% in finishing period. Overall, the experiments suggested a higher optimum SID Trp:Lys ratio than is currently standard practice. The regression analysis from the meta-analysis showed that increasing dietary NE improved ADG and G:F. However, the magnitude of improvement will be minimized if the SID Lys concentration is limiting. The validation experiments indicated that the prediction equations provided a good estimation of growth rate and feed efficiency of growing-finishing

pigs fed different levels of dietary NE except for pigs fed the diet with DDGS. These predictions of growth performance can then be used to model economic value of different dietary energy strategies.

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Dedication

To Mom & Dad

Chapter 1 - A Review of Tryptophan Requirements in Nursery, Growing, and Finishing Pigs

1.1 Expression of amino acid requirements

The ideal amino acid pattern is a standard reference when evaluating the quality of dietary protein (Wang and Fuller, 1989). The NRC (2012) defines the ideal amino acid profile as one whose patterns contain the optimum balance of all amino acids required for maintenance and productive functions for a clearly defined physiological state. This concept has been applied to define the optimal amino acid content in diets for pig varying in BW. Because not all protein is fully digested, absorbed, or available for metabolism, the most accurate assessment of amino acid content in a feed ingredient or expressing an animal's requirement are in form of bioavailable amino acids. Batterham (1992) described the slope-ratio assay as a method to assess the bioavailability of amino acids. In this type of test, increasing amounts of a limiting amino acid are fed and the change in growth performance is measured compared to an increasing amount of a control ingredient with known availability. However, the bioavailability determined from this assay is only a relative value which is highly variable among experiments. The major disadvantage of this method is that it is expensive, time-consuming, and the values are not additive for the mixture of feed ingredients (Batterham, 1992). Therefore, amino acid digestibility has been used to represent the bioavailability based on an assumption that the digested and absorbed amino acids in the small intestine can be used for the protein synthesis. The digestibility can be expressed as the total tract (fecal) digestibility and ileal digestibility. The total tract digestibility measures the proportion of ingested amino acid to that excreted in feces.

However, due to the effect of microbial fermentation in the hind-gut, total tract amino acid digestibility will overestimate an amino acid's digestibility.

Because amino acids are only absorbed at the small intestine, determining ileal digestibility gives a more accurate estimation of bioavailability (Stein et al., 2007). Ileal digestibility is expressed as apparent or standardized amino acid digestibility depending if the contribution of ileal endogenous losses is taken into account. The apparent ileal digestibility (AID) is determined by the disappearance of ingested amino acid from the proximal intestine prior to the distal ileum. As in its definition, the ileal endogenous amino acid losses are not considered which resulted in an increase of AID of the amino acid in a nonlinear manner with increase of dietary amino acid (Figure 1.1).

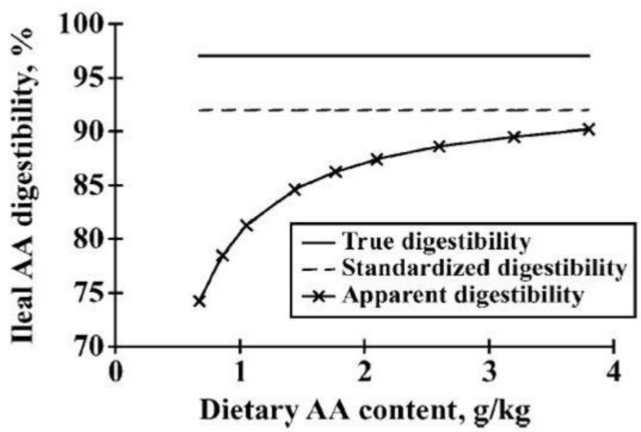

Figure 1.1 Influence of amino acid content on true, standardized, and apparent ileal amino acid digestibility (Stein et al., 2007)

The primary disadvantage of AID is that it does not consider endogenous amino acid losses. In true ileal digestibility (TID), the endogenous amino acid losses are subtracted from the total ileal outflow, thus being a more accurate estimate of an amino acid's digestibility. Several procedures have been developed to measure the total ileal endogenous amino acid losses including a homoarginine technique and the isotope dilution technique (Stein et al., 2007). These techniques are laborious, costly, and require highly specialized equipment, consequently, the TID of amino acids in a feed ingredient are not regularly measured. An alternative to TID is standardized (SID) ileal amino acid digestibility where the basal endogenous amino acid losses are subtracted from the total ileal outflow. Therefore, the SID of amino acids has been established in a wide range of feed ingredients for swine (CVB, 2003; INRA-AFZ-INAPG, 2004; NRC, 2012). Standardized ileal digestible amino acids have been applied in practical feed formulation to improve ingredient usage and to accurately meet the amino acid requirements for pigs. Accordingly, SID amino acids have become the standard practice in the United States for practical diet formulation.

1.2 Amino acid as a ratio to lysine

Pig performance is dictated by the extent of a limiting amino acid in the diet relative to its requirement. Cromwell (2004) identified the limiting amino acids in complex and cereal grain-based diets using the nitrogen excretion as a criteria (Table 1.1). Lysine was found to be the first limiting amino acid in most of the cereal-grain type diets including a typical, corn-soybean meal-based, diet followed by threonine and tryptophan as the second and third limiting amino acids, respectively. Accordingly, several studies have been conducted to determine the lysine requirement as an amount per day (g/day), amount per unit of metabolic body weight (g/BW$^{0.75}$), amount of unit per protein accretion, amount per unit of dietary energy, or as a percentage of the diet. Nonetheless, in most diet formulations, the lysine requirement is defined in a ratio to dietary energy (lysine:calorie ratio; Main et al.(2008)) in order to ensure proper lysine intake as dietary energy density changes (Ellis and Augspurger, 2001). Also, because the lysine requirement changes with BW, the lysine:calorie ratio is determined as a function of pig BW range (Main et al., 2008).

For other amino acids, the common practical method to express the requirements is in terms of a SID amino acid to lysine ratio. This provides an automatic adjustment to the requirement estimates if the lysine to calorie ratio is changed. Therefore, when formulating diets, one must first determine the most economical dietary energy content, then the dietary lysine content is calculated from the lysine:calorie ratio, and third, concentrations of other amino acids are adjusted to provide the proper ratio relative to lysine.

Table 1.1 Limiting amino acid in selected feed ingredients, simple diets, and complex diets for swine (Adapted from Cromwell, 2004)[1]

	Limiting amino acids				
Feedstuff	First	Second	Third	Forth	Fifth
Cereal grains					
Corn	Lys	Trp	Thr	Ile	Val
Sorghum	Lys	Thr	Trp	M+C	Val
Wheat	Lys	Thr	(Ile	Val	M+C)
Barley	Lys	Thr	Trp	Ile	Val
Oats	Lys	Thr	Trp	Ile	Val
Protein sources					
Soybean meal	M+C	Thr	Lys	Val	Trp
Canola meal	Lys	(Thr	Trp)	(Ile	Val)
Meat and bone meal	Trp	M+C	(Thr	Ile	Lys)
Blood meal	Ile	M+C	Thr	Lys	Trp
Fish meal	Trp	(Thr	M+C)	Val	Ile
Miscellaneous					
Dried plasma	Ile	M+C	Lys	(Thr	Val)
Dried whey	M+C	(Lys	Val)	Trp	Thr
Simple diets					

Corn-soybean meal	Lys	Thr	Trp	M+C	Val
Corn-canola	Lys	Trp	Thr	Ile	Val
Corn-fish meal	Trp	Lys	Thr	Ile	Val
Sorghum-soybean meal	Lys	Thr	M+C	Trp	Val
Wheat-soybean meal	Lys	Thr	(Ile	Val	M+C)
Barley-soybean meal	Lys	Thr	M+C	(Ile	Val)
Complex diet					
Corn-soybean + 30% dried whey	M+C	Lys	Thr	(Trp	Val)
Corn-soybean + 25% whey + 6% animal plasma	M+C	Thr	(Trp	Val)	Lys

[1]Amino acids within parentheses are nearly equally limiting.

1.3 Determining the amino acid requirement

The concept of a requirement is defined as the nutrient level that results in the maximum predicted response. From this concept, the amino acid requirements of swine have been empirically determined by feeding graded level of amino acid (dose) in a basal diet that is deficient in that amino acid. The responses are measured and the level that produces the maximum response is determined as the requirement. A typical pattern in these dose response studies is to generally have an ascending portion where the amino acid in question is limiting the response. Then when the amino acid reaches its requirement, a plateau occurs where the maximum (minimum) performance is observed. In some cases, a decline in response may be observed after the plateau period due to a negative or toxic effect from an amino acid excess (Pesti et al., 2009). Several mathematical models have been used to fit this relationship with the ultimate goal to define the specific level that provides the ideal response. Pesti et al. (2009) described several mathematical methods to estimate nutritional requirement from experimental data (Figure 1.2).

The paired t-tests is considered to be the simplest method to compare the response of feeding two levels of amino acids where the lowest level that provides similar response to the maximum response is considered the requirement. The major drawback of this method is the low power to detect the significant difference and the high likelihood of type II error that would result in an underestimation of the requirement. Due to the low power and the lack of describing a pattern, the t-test method is rarely used in current amino acid requirement studies. A more frequently used model is the polynomial (quadratic) model that illustrates an increasing of response at a decreasing rate until the maximum is achieved and the further increase beyond maximum results in a predicted reduced response. The quadratic response is useful for describing decreases in response due to excesses.

The most common model that has been used in requirement studies is the broken-line linear model that depicts a constant rate of increasing response (linear ascending) until a linear plateau portion is reached. This results in a break point between the two linear lines where the requirement is determined (Robbins et al., 2006). The accurately defined point is easy to interpret, making this a preferred method by many scientists. The concern of this model is that the linear ascending portion does not resemble the typical biological response in which a diminishing rate of increase in performance is observed prior to the point of maximum response. This can be overcome with a curved ascending portion and a smooth transition to the plateau, defined as the broken-line quadratic model. In the broken-line quadratic model, the log function is used to transform the curved ascending portion into a straight line; then the break point with plateau region is determined as the requirement. Nevertheless, the plateau portion of both broken-line models does not have a feature to describe when the negative effect of excessive nutrient exists.

Non-linear models are also used with an aim to provide a better fit of the responses that have non-constant rates of increase or decrease. One of the non-linear models that frequently used is the curvilinear model. Baker (1986) described the curvilinear model of growth response to essential nutrients as a shape that has a lesser slope at doses between 0 to 30% of the maximum growth, a constant (and maximal) slope between 30 and 70% of the requirement, and a decreasing slope between 70 to 100% of the maximum growth. Baker (1986) explained the decrease of slope beyond 70% is due to the animal in a population that required the least amount of amino acid has achieved its requirement. The continuing decrease of slope depicts that the requirement of more and more animals in the population is met. Another non-linear model is the saturation kinetics model (sigmoid model) that is similar to the curvilinear model but has a sigmoid shape in the ascending portion. However, this model rarely fits the response from an animal feeding trial (Pesti et al., 2009). In non-linear models, the response still increases in smaller increments in the plateau portion as the maximum response is approached; however, the maximum is never reached (asymptotic). Because of this feature, the non-linear models can neither distinguish the toxic level of nutrient nor define a specific point where the maximum response lies. Therefore, it depends on the researcher to set an arbitrary percentage of the asymptotic maximum and define the response at this point as the requirement. The use of 90 or 95% of the asymptotic maximum as a requirement has been suggested (Baker, 1986; Robbins et al., 2006; Quant et al., 2012).

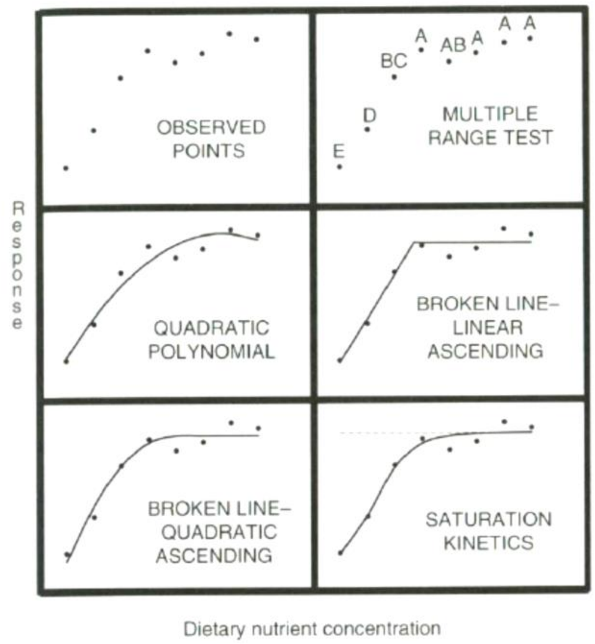

Figure 1.2 Mathematical models determining the nutrient requirement (Pesti et al., 2009)

It is apparent that there are a variety of mathematical methods to determine a nutritional requirement. The polynomial (quadratic) model is the easiest to fit the data, as only 3 increments of a nutrient need to be tested while the broken-line and non-linear models require more data points distributed over a wide rage to define the relationship (Gahl et al., 1994). There are no concrete rules to choosing among these models. Therefore, the decision relies on the researcher's judgment to select a model that best fits their experimental data. This can result in a wide range of requirement estimates for the same nutrient. Baker (1986) found 27% variation in the requirement estimate while using 4 different mathematical methods in a histidine requirement study in chickens. Pesti et al. (2009) also demonstrated a large difference (32%) between the highest and lowest lysine requirement (g/kg) in broiler from applying 4 mathematical methods on the same data set. Undoubtedly, the choice of statistical model is critical for characterizing the requirement.

1.4 Determining the tryptophan requirement

Tryptophan is the third limiting amino acid after lysine and threonine in many swine diets based on corn and soybean meal (Table 1.1). The tryptophan requirement in pigs has been evaluated since the 1970's and researchers are still evaluating the requirement as diet composition and swine genetics continue to change. The extensive use of crystalline amino acids in the diet to optimize feed cost and to reduce nitrogen excretion has stressed the importance of accurately defining the tryptophan requirement. Also, the optimal dietary tryptophan requirement has received considerable attention recently because of the use of dried distillers grains with solubles (DDGS), the by-product of ethanol production from corn. This is because of the low tryptophan concentration in corn and subsequently in DDGS relative to other amino acids.

In weanling pigs, the determined tryptophan requirement observed from 23 experiments since 1975 vary considerably (Table 1.4). The majority of the studies expressed the requirement as a concentration in the diet (% or g/kg) that ranged from 0.12 to 0.14% TID tryptophan, 0.15 to 0.21% AID tryptophan, 0.18 to 0.21% SID tryptophan, and 0.14 to greater than 0.23% total tryptophan. The minority but more recent studies expressed the tryptophan requirement as a ratio to lysine that found a requirement of 13 to 15% AID tryptophan:lysine ratio or 15 to 19.5% on SID basis. Recently, Simongiovanni et al. (2012) summarized the SID tryptophan:lysine ratio requirement in weaned pigs (7- to 25-kg BW) from the data of 37 studies. They standardized the level of tryptophan and lysine on a SID basis by recalculating the amino acid profile of the diets based on ingredient values from INRA-AFZ (2004). They estimated the SID tryptophan:lysine ratio requirement of 17, 22, and 26% using linear-plateau, curvilinear-plateau, and asymptotic models, respectively. The NRC (2012) suggests a tryptophan requirement at 16 to 17% of SID lysine.

A wide range of tryptophan requirements is also estimated for growing-finishing pigs. Susenbeth (2006) collected data from 33 dose-response studies evaluating the tryptophan requirement in growing pigs. They defined the optimum tryptophan:lysine ratio as the beginning of the plateau phase using feed intake and BW gain as response criteria. The minimum ratio of 13.6% and the maximum of 21.3% were observed in 33 studies and resulted in a large between trial standard deviation. The estimated tryptophan requirement observed from 29 experiments since 1983 in growing-finishing pigs is presented in Table 1.5. Similar to the nursery, the majority of studies defined the tryptophan requirement as a concentration in diet that ranged from 0.09 to 0.17% TID tryptophan, 0.08 to 0.20% SID tryptophan, or 0.08 to 0.20% total tryptophan, whereas the minority reported the tryptophan as a ratio to lysine from 16 to 23.6 % and 14 to 22 % on SID and TID basis, respectively.

It is difficult to compare requirement estimates among studies when the tryptophan level is expressed on a different basis. Expressing tryptophan requirement on an SID basis as a ratio to lysine would reduce this variation due to differences in digestibility or a limitation of lysine or energy intake. However, the observed SID tryptophan:lysine ratio requirements still vary considerably among trials. Several factors could be responsible for the diversity of tryptophan requirements among studies. First, the requirement of an amino acid is the combination of requirement for protein accretion and that of maintenance. It has been demonstrated that the optimum tryptophan to lysine ratio is greater for maintenance than for protein accretion (Fuller, 1994). Therefore, when protein accretion decreases as the pig becomes heavier a higher tryptophan:lysine ratio requirement may be needed relative to a young, rapidly growing pig (Susenbeth, 2006). This is in agreement with NRC (2012) that recommends an increasing SID tryptophan:lysine ratio as pigs become heavier (Table 1.2).

Table 1.2 The SID tryptophan:lysine ratio calculated from the recommended SID lysine and tryptophan for each BW range from the nutrient requirement of swine (NRC, 2012).

BW range, kg	5-7	7-11	11-25	25-50	50-75	75-100	100-135
SID lysine, %	1.50	1.35	1.23	0.98	0.85	0.73	0.61
SID tryptophan, %	0.25	0.22	0.20	0.17	0.15	0.13	0.11
SID tryptophan:lysine ratio, %	16.7	16.3	16.3	17.3	17.6	17.8	18.0

Nevertheless, Susenbeth (2006) investigated the potential factors (BW, BW gain at the beginning of plateau, lysine and crude protein content, year of publication) affecting optimal tryptophan:lysine across 33 studies in growing-finishing pigs and showed that the optimal tryptophan:lysine did not have a relationship with BW in the meta-analysis. Although, it should be noted that due to the large trial to trial variability for requirement estimates it is unlikely from a statistical standpoint this analysis would find the subtle increase in ratio as BW increases.

Secondly, the criteria of response also are crucial when determining amino acid requirements. There appears to be a hierarchy of amino acids requirement estimates. A number of experiments found that using daily gain and feed intake as criteria for tryptophan requirement resulted in a higher estimate than using feed efficiency (Burgoon et al., 1992; Eder et al., 2003; Susenbeth, 2006; Petersen and Stein, 2012). The optimum requirement for decreased PUN was lower compared to using feed efficiency in several studies (Guzik et al., 2002; 2005b; Susenbeth, 2006; Petersen and Stein, 2012). However, the study by Quant et al. (2012) observed a similar estimate obtained from plasma urea nitrogen (PUN) and from growth performance. A small number of studies (n = 2) utilized plasma tryptophan as a response criteria which resulted in a similar optimum tryptophan level as using gain or feed to gain as criteria. Sometimes when multiple response criteria are used, the average of optimal levels across different response variables is used as a representative for the tryptophan requirement.

The effect of tryptophan on carcass characteristics has also been investigated. A low serotonin level in the hippocampal region of the brain was observed in stress-susceptible pigs compared to those that were stress-tolerant. A short term supplementation of high tryptophan dosage (0.5% tryptophan) has been shown to decrease stress by elevating serotonin and reducing the incidence of pale, soft, and exudate (PSE) pork (Adeola and Ball, 1992; Pettigrew and Esnaola, 2001). Nevertheless, feeding tryptophan at the nutritional requirement has not been shown to have a benefit on pork quality (Henry, 1995; Guzik et al., 2006; Kendall et al., 2007). A greater carcass lean percentage, lower backfat depth, and improved carcass yield were observed in several tryptophan titration studies (Mohn and Susenbeth, 1994; Guzik et al., 2005b; Nitikanchana et al., 2011b; c; 2013; Salyer et al., 2013) whereas some studies did not show a significant improvement in carcass characteristics with increasing tryptophan (Batterham and Watson, 1985; Kendall et al., 2007; Salyer et al., 2013). In most of these studies (Mohn and Susenbeth, 1994; Guzik et al., 2005b; Nitikanchana et al., 2011b; c; 2013), carcass yield and leanness responses to increasing tryptophan did not reach plateau even with the highest tryptophan content that used in the experiments. The study by Guzik et al. (2005b) also showed a greater tryptophan requirement for carcass fat free lean than the requirement for growth rate or feed efficiency with using the broken-line analysis. Although variable these observations may suggest a higher tryptophan content to maximize carcass value compared to the level for maximum growth.

Thirdly, in addition to protein accretion, tryptophan is also involved in the production of serotonin (5-hydroxytryptophan, 5-HT) as well as immune response regulation through the kynurenine pathway (Figure 1.3).

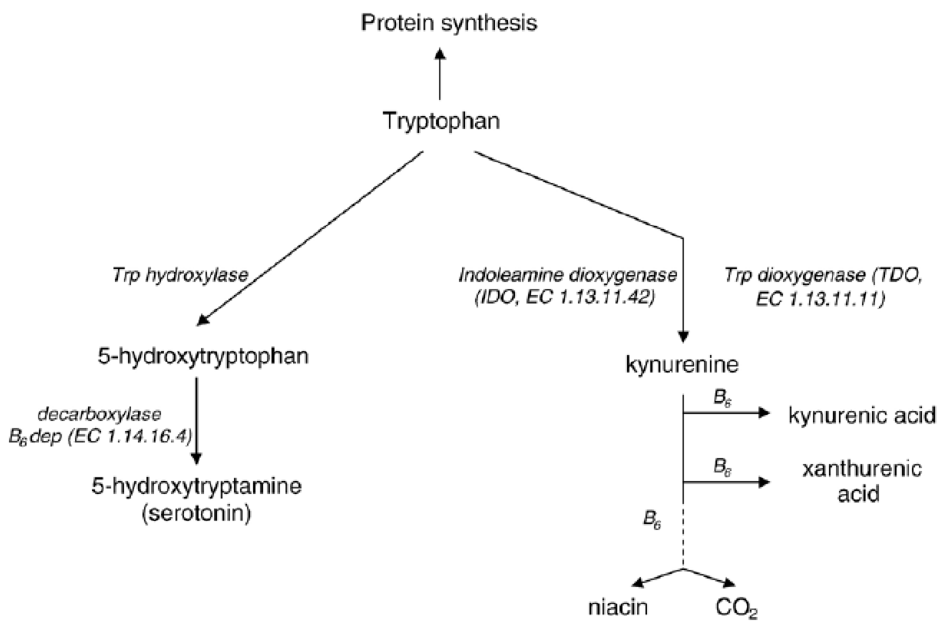

Figure 1.3 Metabolic pathways of tryptophan (Le Floc'h and Seve, 2007)

During an inflammatory event, cytokines activate the enzyme indoleamine 2,3 dioxygenase (IDO) resulting in increased tryptophan catabolism via the kynurenine pathway (Le Floc'h and Seve, 2007). This results in competition between the use of tryptophan for growth and the immune system. Therefore, it is hypothesized that the availability of tryptophan for growth is compromised when animal's immune defense is activated. Le Floc'h et al. (2009, 2010) have conducted series of experiments to define the modification of tryptophan requirement associated with immune function by developing a moderate inflammation in post-weaning pig through poor sanitary housing. They fed high and low levels of tryptophan in good and poor sanitary housing and found that pigs fed high tryptophan had improved growth performance regardless of sanitary condition. A follow up trial was conducted with a range of SID tryptophan:lysine ratios from 15 to 24% which they found improved growth rate with increasing tryptophan resulting in a plateau of response at 20.3% SID tryptophan:lysine ratio in either sanitary condition. Therefore, Le Floc'h et al. (2010) concluded that moderate inflammation did not modify the tryptophan requirement in post-weaned pig. Nevertheless, De Ridder et al. (2012) conducted a trial to estimate the partial efficiency of tryptophan utilization for whole body protein deposition in immune stimulated (injection of *E.coli* lipopolysaccharide) growing pigs. They observed a reduction in efficiency of tryptophan utilization for protein deposition and concluded that the tryptophan requirement was increased approximately 7% during an immune challenge. Based on these results, it is still unclear whether tryptophan requirement elevates when pigs' health is challenged. The role of tryptophan on immune response and its impact on requirement for growth still needs to be further investigated.

Fourth, the mathematical model selected to interpret the experimental data is also influential in determining a requirement estimate. Different mathematical methods can lead to different interpretation of the results (Table 1.3). In general, the broken-line linear model usually under-estimates the tryptophan requirement compared with using the broken-line quadratic model (Petersen and Stein, 2012; Quant et al., 2012). Conversely, the curvilinear or quadratic model estimate a higher requirement compared to the broken-line models (Burgoon et al., 1992; Petersen and Stein, 2012; Zhang et al., 2012). Petersen and Stein (2012) used the broken-line, quadratic, and the intercept of the broken-line and quadratic analysis to determine the SID tryptophan:lysine ratio requirement. They observed estimates ranging from 20.1 to 26.1%, 19.5 to 24%, and 16.7 to 19.1% of lysine across 3 mathematical models using ADG, G:F, and PUN as the response criteria, respectively.

Table 1.3 The SID tryptophan:lysine ratio (%) requirement from the broken-line, quadratic, and the intercept of the broken-line and quadratic analysis using ADG, G:F, and PUN as the response criteria (Petersen and Stein, 2012)

	Response criteria		
Mathematical model	ADG	G:F	PUN
Exp. 1			
Broken-line	20.1	19.5	16.7
Quadratic	26.1	24.0	19.1
Intercept of the broken-line and quadratic analysis	22.2	22.1	18.6
Exp. 2			
Broken-line	18.1	17.4	17.0
Quadratic	21.5	20.1	19.3
Intercept of the broken-line and quadratic analysis	20.0	18.9	18.6

Fifth, as with other essential amino acids, the success of determining tryptophan:lysine ratio requirement depends on the lysine concentration in the diet. Lysine has to be the second limiting amino acid in the diet in order to accurately determine the tryptophan requirement as a ratio to lysine. When lysine is over the requirement the excess is not used for protein accretion; therefore, there is no further improvement with feeding higher tryptophan:lysine ratio such that the optimal tryptophan:lysine is underestimated (Susenbeth and Lucanus, 2005). Formulating dietary lysine slightly below the pig's requirement ensures the maximum utilization of both lysine and tryptophan that ultimately results in a more accurate tryptophan:lysine requirement estimate.

When performing an amino acid titration study, the dietary levels of other essential amino acids is also imperative. One concern is that some other essential amino acids could be inadequately supplied such that it becomes the second-limiting amino acid instead of lysine which can result in an underestimation of the requirement. Thus, other essential amino acid levels in the basal diet should be critically evaluated to ensure the adequate levels of other amino acids are provided. Typical standard research practice is to formulate these other amino acids at a minimum of 105% of the requirement ratio relative to lysine (Guzik et al., 2002; Zhang et al., 2012).

When an excess amount of other essential amino acids are provided they may lead to an amino acid imbalance which can result in decreased feed intake and consequently affect the growth response (Henry et al., 1992; Henry et al., 1996; Baker, 2005). However, this is not usually a large concern unless large excesses are provided. It is well documented that the large neutral amino acids (LNAA) which includes branched-chain amino acids (isoleucine, leucine, and valine) and aromatic amino acids (phenylalanine and tyrosine) share a common transport system with tryptophan resulting in a competitive absorption at the intestine and blood-brain barrier (Henry and Seve, 1993). Therefore it is hypothesized that the high level of LNAA in the diet will elevate the requirement of tryptophan as a decreased tryptophan from the diet is being utilized. Henry et al. (1992, 1996) found decreased growth rate and feed intake when LNAA was increased in diets at high or low tryptophan, with a greater decrease observed at the low tryptophan level (24 to 32% vs. 5% reduction in growth rate and feed intake at low vs. high tryptophan level). A reduction in serotonin synthesized in the brain is proposed to be responsible for the reduction in feed intake and the subsequent growth performance.

Accordingly, the interaction between LNAA and tryptophan have raised concern for the optimal tryptophan concentration in diets with high DDGS inclusion rate, the by-product of ethanol production from corn, because the low level of tryptophan in corn is amplified whereas the percentage of LNAA increases in DDGS. The nutrients reported in NRC (2012) show that the total LNAA in DDGS is 3.7 times higher (8.3% vs. 2.3%) than in corn or 3.5 times greater (6.7% vs. 1.9%) on SID basis. Currently, there are only a few studies on the tryptophan requirement in diet containing DDGS. In nursery pigs, Ma et al. (2010) and Petersen and Stein (2012) investigated the tryptophan requirement in diets with DDGS inclusion rates of 30 and 20% where they concluded optimum SID tryptophan:lysine ratios of 15.0 and 18.2%, respectively. In grower pigs, Hinson et al. (2010) and Salyer et al. (2013) concluded that a 16 to 16.5 % SID tryptophan:lysine ratio was optimal for less than 70 kg pigs fed 30% DDGS diet, whereas Ma et al. (2010) found 14.7 % SID tryptophan:lysine to be optimal for 46 to-64 kg barrows fed with high protein distillers dried grain diets. In finishing pigs (greater than 70-kg BW), Nitikanchana et al. (2013) concluded that 20% SID tryptophan:lysine was required which agreed with Salyer et al. (2013) that concluded the requirement was greater than 19.5%. However, Ma et al. (2010) and Hinson et al. (2010) indicated a considerably lower requirement (14 to 16% SID tryptophan:lysine) for finishing pigs fed high level of DDGS. The tryptophan requirement of pig fed DDGS diets seemed to be higher than the corn-based diets. However, the requirement estimate is variable among trials and needs to be further investigated.

Accurate amino acid content in feed ingredients is needed to formulate diets at the desired amino acids levels. Ideally, the ingredient samples that will be used in the trial will be properly sampled and accurately analyzed for tryptophan and lysine content, along with other amino acids in order to accurately formulate the test diets. Unfortunately, the analysis of tryptophan content is not consistent. Cromwell et al. (1994) observed that the variability of tryptophan concentration among laboratories (10% coefficient of variation; CV) was greater than the variability among sources (5% CV) of corn and soybean meal. Therefore, the difficulty analyzing tryptophan in diets and ingredients may be partially responsible for the variation in requirement estimates among the published papers (Susenbeth, 2006).

Sixth, an interaction between tryptophan level and gender on growth performance of growing-finishing pigs has been reported in several studies. Henry et al. (1995) found a greater reduction in growth rate, feed intake, and gain to feed in gilts fed tryptophan-deficient diet than in barrows that fed the same diet. The greater sensitivity of reduction in growth rate and feed efficiency in gilts than in barrows was repeated in the subsequent trial that increased crude protein by 4% in the tryptophan-deficient diet (Henry et al., 1996). The recent tryptophan requirement study by Salyer et al. (2013) also supported these findings that gilts had greater daily gain response to increasing tryptophan in high protein diet compared to barrows. Gilts have a higher lysine requirement than barrows (Main et al., 2008; NRC, 2012) and typically are fed diets closer or slightly under their requirements. Therefore, one possible explanation for the greater response is that the provided lysine was probably farther under the requirement of gilts than barrows that supplementation resulted in a greater benefit. The greater magnitude of response to increased tryptophan level in gilts found in several studies suggests more power to detect the dose-response relationship in a tryptophan requirement study when using gilts.

Seventh, the tryptophan requirement in studies using non-corn based (wheat-barley) diets has been observed to be higher than the requirement in diets that are corn-based. Accordingly, the ideal study on the influence of diet composition on the tryptophan requirement is to feed varying tryptophan levels in different basal diet types to the same group of pigs. However, there have not been any studies reported the requirement across diet types evaluated in this manner. As mentioned previously it is difficult to compare the tryptophan requirement estimates in corn vs. non-corn based diets that obtained from different studies due to the large study to study variability among experiments. The closest studies that indirectly compared requirements based on diet type were performed by Jansman et al. (2010) and Quant et al. (2012). For the 9- to 24-kg BW pig using either corn or non-corn (Barley-pea-wheat) based diets, Jansman et al. (2010) observed the same tryptophan requirement. Using 25- to 50-kg BW pigs fed corn-soybean meal or wheat-barley-soybean meal based diets, Quant et al. (2012) found a similar requirement regardless of the diet type. Therefore, based on these findings, it appears that tryptophan requirement is independent of the diet composition.

Finally, the procedure used in mixing experimental diets can play a role in the variation of tryptophan requirement among studies. The individual mixing of experimental diets is generally utilized; however, it is time-consuming and laborious for a requirement study where numerous diets are needed. In tryptophan requirement studies, increasing doses of crystalline L-tryptophan are usually added to a basal diet to achieve the desirable dietary tryptophan levels while other ingredients are maintained. Therefore, the only components that change between diets are the amount of crystalline L-tryptophan and the amount of ingredient that it replaced such as corn or corn-starch. Because of this similarity between diets, one way to reduce diet variability is to manufacture large batches of high and low tryptophan diets that can be blended in a predetermined proportion to create the intermediate tryptophan level diets. The reduction of ingredient handling by this method would help to avoid mixing error when making each individual batch. However, these blending methods can be limited by batch sizes of the basal diet and bin capacity to store basal diets especially in commercial scale finishing trials that may require several hundred tonnes of feed. One alternative is to blend diets on farm using the robotic feeding system capable of providing and measuring feed amounts for individual pen. However, this method will be limited by the accuracy of the blending system. Therefore, the negatives and positives of different test diet manufacturing methods need to be carefully considered when doing any tryptophan or amino acid dose titration study.

1.5 Law of diminishing returns in amino acid requirement studies

Results from several amino acids requirement studies agree with the law of diminishing return. These studies demonstrate a decrease in rate of increasing gain as equal increments of nutrients are added to the diet near maximum gain (Almquist, 1953; Gahl et al., 1994). Gahl et al. (1995) conducted a lysine requirement study in growing pigs that eloquently demonstrates this concept. In this study, the weight gain was plotted to the increment of lysine intake, and the first derivative of the curve was then calculated to represent the efficiency for retention of gain for each increment of lysine added to the diet or the "marginal efficiency" (Figure 1.4).

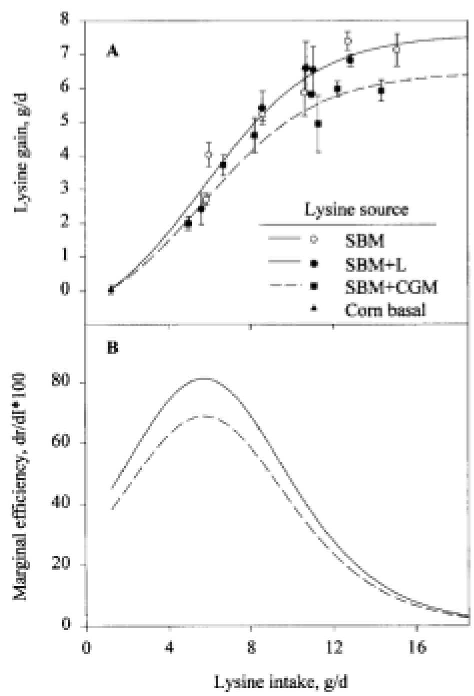

Figure 1.4 Diminishing return in gain of pig fed diet with graded concentration of lysine (Gahl et al., 1994)

The results showed that after the marginal efficiency reached maximum, it continued to diminish and approached zero as the plateau in gain (maximum gain) was approached. It is apparent that the output of gain per unit of amino acid added in the diet is not constant but is diminishing over a large portion of the response range. This suggests that the best profit of additional gain may not necessarily be at the amino acid level that provides the maximum gain.

1.6 Economic implications to determine the optimal amino acid level

Although the biologic responses that have an impact on economics are selected to identify the nutrient requirement, the nutrient level that provides the maximal response may not reflect the highest net profit. Obviously, the impact of feeding different amino acid levels expressed in monetary units has to be considered. The conventional parameters used to evaluate the impact on economics in swine industry are the total feed cost per pig and the feed cost per kg of gain. However, total feed cost per pig only accounts for the input (feed) cost but not the output (gain) from feeding different nutrients which clearly has a significant impact on profit. The feed cost per kg of gain accounts for outcome expressed in gain and feed efficiency by dividing the total feed cost per pig by the total kg of body weight gain. Therefore, the high feed cost from addition of amino acids can be offset by the improved weight gain; conversely, low weight gain can be compensated by low feed cost. Nevertheless, this method fails to reflect the net profit margin as the impact of amino acids on other criteria such as rate of gain or carcass quality.

Partial budgeting is a widely used decision-making agricultural economics tool to compare the costs and benefits of alternative strategies. The concept is to only focus on both income and expense parameters that are changed due to implementation of a specific alternative (Roth and Hyde, 2002). From this concept, the income over feed cost (IOFC) method has been developed to evaluate dietary scenarios and has been demonstrated as a better parameter than total feed cost or feed cost per unit of gain (De La Llata et al., 2001). In this method, feed cost per pig is the expense that is driven by feed cost and feed efficiency which is then subtracted from the gross income per amount of weight gain which is derived from rate of gain to represent the IOFC. Gross income per pig is the income from selling one pig that can be calculated from the weight gain multiplied by the market price. Generally, the the carcass price is used to calculate the income; however, carcass weight can also be calculated from live weight at market or live weight gain multiplied by carcass yield percentage. The premiums and discounts from the carcass measurement can also be included in the gross margin to reflect the impact of diet on carcass quality. These values are quite variable since each packing plant has its own adjustment grid for the premiums and discounts. When analyzing IOFC for finishing pigs, different marketing strategies that market pigs at the same time or at similar body weight have to be considered (Main et al., 2005). The diet that results in a greater rate of gain will achieve a heavier body weight at the same market and a more revenue from the heavier weight when market date is fixed (De La Llata et al., 2001a). On the contrary, if pigs are sold at the same market weight, the period on feed will be different for each group of pigs that has different growth rates. As a consequence, feed cost and facility cost for the extra days on feed have to be justified. The use of IOFC also allows a dynamic evaluation of the economics. This would permit the producer to formulate diets at a nutrient level that maximizes the profit as the price of revenue or feed ingredients change over time.

Up to present, only a few studies (Nitikanchana et al., 2011a; Young et al., 2013) have implemented the economics evaluations to determine the optimal tryptophan level. Nitikanchana et al. (2011a) fed 14.7 to 24.0% SID tryptophan:lysine ratio to 6- to 11-kg pigs and found a quadratic improvement in G:F with increasing tryptophan which suggested a diminishing return to additional tryptophan inputs as the maximum response is approached. The best growth performance and IOFC in this study was observed at 20.3% SID tryptophan:lysine and only a small reduction in IOFC was presented at 22.1%. However, feeding below 20.3% resulted in a great reduction of economic return (Figure 1.5). These data suggests that feeding slightly beyond the tryptophan requirement neither decreased growth performance or economic return.

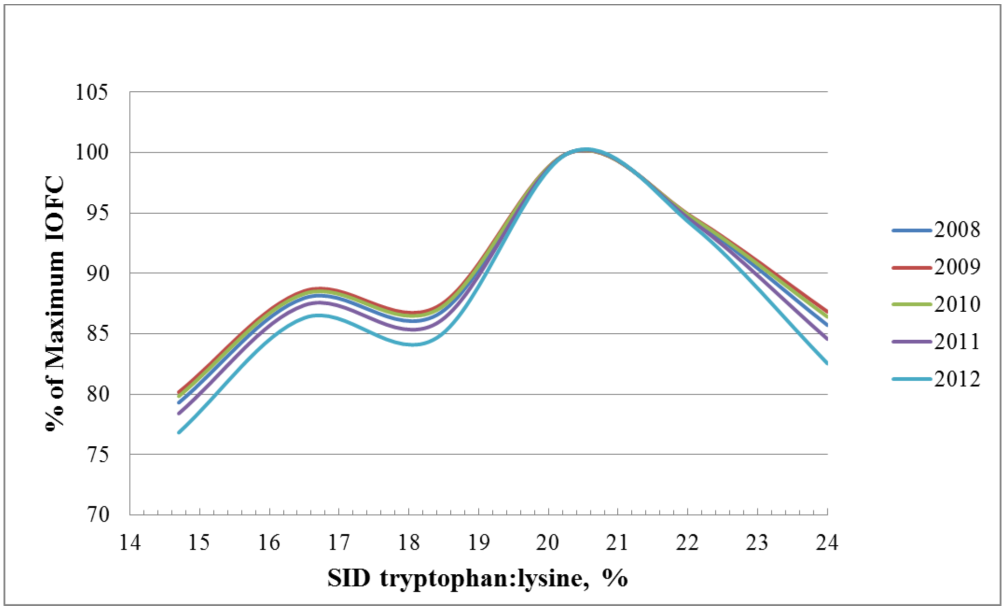

Figure 1.5 Income over feed cost of feeding SID tryptophan:lysine ratio using corn and soybean meal prices from 2008 to 2012 (Nitikanchana et al., 2011a)

The study by Nitikanchana et al. (2013) titrated 16 to 22% SID tryptophan:lysine ratio in finishing pigs also showed a diminishing rate of return in growth as SID tryptophan:lysine ratio increased to 20%. The best IOFC was observed at 20% SID tryptophan:lysine with soybean meal as a source of tryptophan but at 18% when using crystalline L-tryptophan as the source of tryptophan (Figure 1.6). Also, feeding at 18 or 20% SID tryptophan:lysine with soybean meal or crystalline L-tryptophan only led to a 4 to 5% reduction in IOFC while up to 12% reduction was observed with feeding outside this range.

The diminishing return of feeding tryptophan that was observed in these studies stresses the importance of determining the response in monetary unit. The economics of feeding different levels of tryptophan depend on both feed cost and value of pig which are unique in each circumstance; therefore, the economic evaluation should be investigated at the time of use to maximize profit.

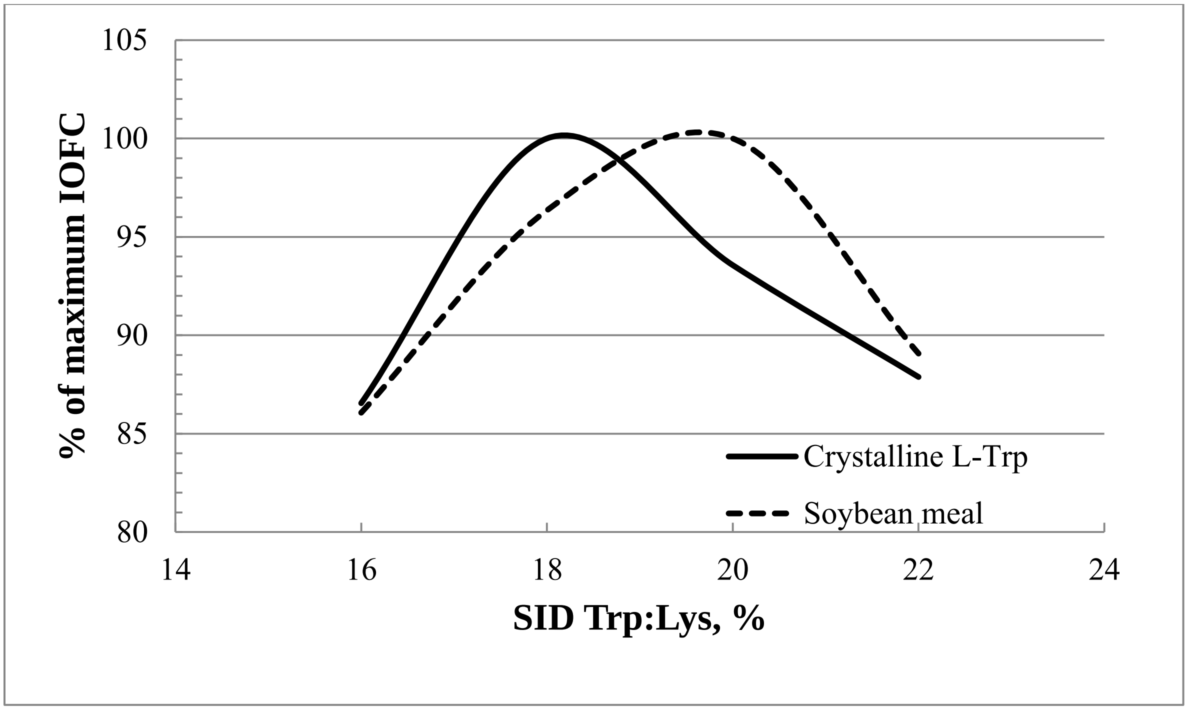

Figure 1.6 Income over feed cost of feeding SID tryptophan:lysine ratio (Nitikanchana et al., 2013)

SUMMARY

The tryptophan requirement as a ratio to lysine on SID basis is desirable for practical feed formulation. However, the tryptophan requirement is not conclusive as the estimated requirements vary considerably due to the variation in experimental and analytical methods among the studies. Traditionally an amino acid requirement is defined as the nutrient level that results in the maximum performance based on a given set of biologic response criteria such as ADG or G:F. Nevertheless, the return of gain per unit of amino acids added in the diet is not constant but is diminishing in a large portion of the response range. Therefore, to serve the ultimate goal of swine producer, the economics of feeding additional tryptophan is critical to identify the optimum concentration in feed formulation.

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Table 1.4 Summary of published studies on tryptophan requirement of nursery pigs[1]

Exp.	Author	Year	BW, kg	Diet type	Trp Source[2]	Parameter[3]	Mathematical tool[4]	Requirement[5]
1	Zimmerman	1975	5-15	Corn-SBM	L-trp	ADG, F:G, PUN[6], plasma trp	Orthogonal contrast	0.153 % total trp
2			5-15	Corn-SBM	Delactosed whey	ADG, F:G, PUN, plasma trp	Orthogonal contras	0.140-0.153% total trp
3	Borg	1986	6-22	Corn-sunflower meal	L-trp	ADG, ADFI, F:G, SUN[7]	Orthogonal contrast	0.16% total trp
4			10-22	Corn-sunflower meal	L-trp	ADG, ADFI, F:G	Orthogonal contrast	0.16% total trp
5	Sato	1987	10-20	Corn-gelatin-corn starch	L-trp	ADG	Broken-line (linear)	0.156% total trp
6	Schutte	1988	10-35	Corn-CGM[8] meat and bone meal	L, DL-trp	ADG	Least square means	> 0.23% total trp
7	Burgoon	1992	6-16	Corn-CGM-fish meal	L-trp	ADG, ADFI, G:F	Broken-line, plateau, quadratic	0.19% total trp
8	Han	1993	10-20	Corn-whey-FM[9]	L-trp	ADG, G:F	Broken-line	0.124 - 0.137% TID trp
9			10-20	Corn-whey-FM	L-trp	ADG, G:F	Broken-line	0.128 - 0.137% TID trp
10	Loughmiller	1997	5-9	Corn-SBM-whey	L-trp	ADG, F:G	Orthogonal contrast	15% AID trp:lys
11			11-23	Corn-SBM	L-trp	F:G	Orthogonal contrast	< 13% AID trp:lys

12	Guzik	2002	5-7	Corn-whey-CGM	L-trp	ADG, ADFI, G:F	Broken-line	0.21% SID trp
13			6-10	Corn-pea-whey	L-trp	ADG, ADFI, G:F	Broken-line	0.20% SID trp
14			10-16	Corn-pea-CGM	L-trp	ADG, ADFI, G:F	Broken-line	0.18% SID trp
15	Guzik	2005	7-10	Pea-barley-wheat	L-trp	ADG, ADFI, G:F	Orthogonal contrast	> 19.5% SID trp:lys
16			10-16	Pea-barley-wheat	L-trp	ADG, ADFI, G:F	Orthogonal contrast	> 19.5% SID trp:lys
17	Susenbeth and Lucanus	2005	15-22	Wheat-barley-SBM	L-trp	ADG, ADFI, G:F	No response of increasing trp	
18	Jansman	2010	9-24	Corn-SBM Barley-Tapioca-wheat	L-trp	ADG, ADFI	NLN exponential	0.21 g/kg AID trp
19	Ma	2010	11-22	Corn-SBM-30%DDGS	L-trp	ADG, G:F	Broken-line (linear)	14.9 -15.1 SID trp:lys
20	Nitikanchana	2011	6-11	Corn-SBM-whey	L-trp	ADG, ADFI, G:F	Orthogonal contrast	20.3% SID trp:lys
21	Petersen and Stein	2012	10-20	Corn-CGM-pea	L-trp	ADG, G:F, PUN	Broken-line	16.7 - 20.1% SID trp:lys
							Quadratic	19.1 - 26.1% SID trp:lys
							Intercept of broken-line & quadratic	18.6 - 22.2% SID trp:lys
22		2012	10-20	Corn-HP DDG	L-trp	ADG, G:F, PUN	Broken-line	17 - 18.1% SID trp:lys
							Quadratic	19.3 - 21.5% SID trp:lys
							Intercept of broken-line & quadratic	18.6 - 20% SID trp:lys

23	Simongiovanni[10]	2012	7-25	Corn & mixture of cereal	L-trp, SBM	ADG, ADFI	Broken-line (linear)	17% SID trp:lys
							Curvilinear-plateau	22% SID trp:lys
							Asymtote	26% SID trp:lys

[1]Data from 15 literatures comprising of 23 studies on tryptophan requirement in nursery pigs (5 to 35 kg BW) were summarized in the table.
[2]Source of tryptophan used to add in basal diet to increase tryptophan level.
[3]Response variables used in the study to determine tryptophan requirement.
[4]Mathematical tools to determine tryptophan requirement in each study.
[5]Tryptophan requirement concluded by the author.
[6]Plasma urea nitrogen
[7]Serum urea nitrogen
[8]Corn gluten meal
[9]Feather meal
[10]Meta-analysis of 37 tryptophan requirement studies across various diet types

Table 1.5 Summary of published studies on tryptophan requirement of growing-finishing pigs[1]

Exp.	Author	Year	BW, kg	Diet type	Trp source[2]	Parameter[3]	Mathematical tool[4]	Requirement[5]
1	Russell	1983	18-34	Corn-SBM	L-trp	ADG, F:G	Broken line	0.15-0.17% total trp
2	Henry	1986	15-40	Corn-Herring meal-wood	L-trp	ADG, F:G	Broken-line (linear)	0.158% total trp
3	Burgoon	1992	22-50	Corn-CGM[6]-fishmeal	L-trp	ADG	Broken line, quadratic, plateau	0.10 % AID trp
4			55-97	Corn-CGM-fishmeal	L-trp	Not state	Broken line, quadratic, plateau	0.06% AID trp
5	Mohn & Susenbeth	1994	60-105	Corn-Pea-Barley	L-trp	ADG, N retention	Curvilinear-plateau	0.17-0.20% total trp
6	Eder	2003	25-50	Corn-barley-pea	L-trp	ADFI,ADG,F:G, N retention	NLN exponential	0.148-0.200% SID trp
7			50-80	Corn-barley-pea	L-trp	ADFI,ADG,F:G, N retention	NLN exponential	>0.171% SID trp
8			80-115	Corn-barley-pea	L-trp	ADG,F:G, N retention	NLN exponential	0.084-0.147% SID trp
9	Guzik	2005	75-105	Corn-feather meal	L-trp	ADG,G:F, PUN[7], carcass fat free lean, NPPC kg of lean	Broken-line (linear)	0.104% TID trp
10	Kendall	2007	89-114	Corn-Crystalline aa	L-trp	ADG, G:F	Broken-line (linear)	0.140-0.145% TID trp:lys
11			91-123	Corn-SBM	L-trp	ADG, G:F	Quadratic with asymtote	0.216-0.220% TID trp:lys

14	Hinson	2010	27-45	Corn-SBM-30% DDGS	L-trp	ADG	Broken-line (quadratic)	16% SID trp:lys
15			67-85	Corn-SBM-30% DDGS	L-trp	ADG, F:G	Broken-line (quadratic)	>13.9% SID trp:lys
16			96-117	Corn-SBM-30% DDGS	L-trp	ADG	Broken-line (quadratic)	16% SID trp:lys
17	Ma	2010	46-64	Corn-23.7% HPDDG	Not state	ADG, G:F	Broken-line (linear & quadratic)	0.14% SID trp
18			70-93	Corn-19.3% HPDDG	Not state	ADG, ADFI	Broken-line (linear & quadratic)	0.11% SID trp
19			95-115	Corn-16.7% HPDDG	Not state	ADG	Broken-line (linear & quadratic)	0.11% SID trp
20	Vinyeta	2010	23-50	Not state	Not state	ADG	Broken-line (linear) Broken-line (quadratic)	0.20 % SID trp:lys 0.23 % SID trp:lys
21	Quant	2012	26-50	Corn-pea-SBM	L-trp	ADG, PUN	Broken-line (linear & quadratic)	15.73-15.83% SID trp:lys
22			28.5-50	Barley-pea-corn	L-trp	ADG, PUN	Broken-line (linear) Broken-line (quadratic)	15.29-15.99% SID trp:lys 15.89-16.74% SID trp:lys
23	Van Der Aar	2012	25-55	Not state	Not state	ADG, ADFI, F:G	Broken-line (linear)	20% SID trp:lys
24			55-110			ADG, ADFI, F:G	Broken-line (linear)	19% SID trp:lys
25	Zhang	2012	25-50	Corn-SBM-wheat bran	L-trp	ADG, F:G, SUN[8]	Broken-line (linear) Curvilinear-plateau	19.7-20.8% SID trp:lys 22.6-23.6% SID trp:lys

26	Nitikanchana	2013	71-127	Corn-SBM-30% DDGS	L-trp, SBM	ADG, G:F	Orthogonal contrast	20% SID trp:lys
27	Salyer	2013	36-130	Corn-SBM-30% DDGS	SBM	ADG, ADFI	Orthogonal contrast	16.5% SID trp:lys (36-70 kg BW) > 19.5% SID trp:lys (70 -130 kg BW)
28			66-125	Corn-SBM-30% DDGS	SBM	ADG, ADFI, G:F, FFLI, backfat depth	Orthogonal contrast	16.5% SID trp:lys (36-70 kg BW) > 19.5% SID trp:lys (70-130 kg BW)
29	Young	2013	34-125	Not state	Not state	ADG, G:F, Loin depth, backfat depth, IOFC[9]	Orthogonal contrast	18% SID Trp:Lys

[1]Data from 16 literatures comprising of 29 studies on tryptophan requirement in growing-finishing pigs (18 to 130 kg BW) were summarized in the table.
[2]Source of tryptophan used to add in basal diet to increase tryptophan level.
[3]Response variables used in the study to determine tryptophan requirement.
[4]Mathematical tools to determine tryptophan requirement in each study.
[5]Tryptophan requirement concluded by the author.
[6]Corn gluten meal
[7]Plasma urea nitrogen
[8]Serum urea nitrogen
[9]Income over feed cost

Chapter 2 - Influence of Standardized Ileal Digestible Tryptophan:Lysine Ratio on Growth Performance of 6- to 10-kg Nursery Pigs

ABSTRACT

A total of 255 nursery pigs (PIC 327 × 1050, initially 6.3 ± 0.06 kg and 3-d postweaning) were used in a 28-d growth trial to determine the effects of standardized ileal digestible (SID) Trp:Lys ratio on growth performance. Treatment diets were fed from d 0 to 14 and a common diet was fed from d 14 to 28. The 6 SID Trp ratios were 14.7, 16.5, 18.4, 20.3, 22.1, and 24.0% of Lys. The diets contained 58% corn, 25% soybean meal, and 10% dried whey and were formulated to 1.30% SID Lys. Pigs were allotted on d 3 after weaning with 6 or 7 pigs per pen and 7 replications per treatment. From d 0 to 14, increasing SID Trp:Lys ratio improved ADG (linear, $P = 0.02$) and generated a tendency for improved ADFI (linear, $P = 0.06$) and G:F (quadratic, $P = 0.08$). Although ADG and ADFI were linear, the greatest numeric response was observed at a SID Trp:Lys ratio of 20.3%. From d 14 to 28, when the common diet was fed, ADFI increased (linear, $P = 0.05$) in pigs previously fed increasing SID Trp:Lys ratio, but no differences were found in ADG and G:F. For the overall trial (d 0 to 28), ADG and ADFI increased (linear, $P < 0.03$) with increasing SID Trp:Lys ratio. Gain:feed was unaffected by SID Trp:Lys ratio. Income over feed cost was used to evaluate the economics of feeding increasing Trp from d 0 to 14. The best IOFC was observed at 20.3% SID Trp:Lys where only a small reduction was observed at 22.1% across different pricing scenarios. Thus, the growth performance and economics indicated the optimal SID Trp concentration for 6- to 10-kg nursery

pigs at 20.3% of SID Lys with feeding up to 22.1% neither decreasing growth performances or economic return.

Key words: Amino acid ratio, growth, lysine, tryptophan, nursery pig

INTRODUCTION

Tryptophan is the third limiting amino acid after Lys and Thr in swine diets based on corn and soybean meal (Cromwell, 2004). As crystalline amino acids, including Trp, become more available, they are extensively used to replace the intact protein sources in swine diets to reduce feed cost and N excretion. The optimum Trp requirement in diets can be expressed in different ways; however, the standardized digestible (SID) Trp requirement as a ratio to Lys (Trp:Lys) is the most practical for diet formulation. Unfortunately, the observed SID Trp:Lys ratio requirement varies considerably among studies. The NRC (2012) estimates the SID Trp requirement at 16.3% of Lys for 7-to 11-kg pigs. Guzik et al. (2005) was greater than 19.5% and Simongiovanni et al. (2012) concluded the SID Trp requirement was between 17 to 22% of Lys for 7 to 11 kg BW pigs. Differences among these published studies may be related to diet composition, gender, genetics, or analytical method.

The return in gain per unit of amino acid added in the diet is not constant but is diminishing in a large portion of the response range (Gahl et al., 1994). Accordingly, the impact of feeding different amino acid ratios expressed in monetary terms has to be considered to serve the ultimate goal to maximize profit. However, the economics of increasing Trp have not been evaluated in the previous studies. Thus, the objective of the study is to examine the SID Trp:Lys ratio requirement and its economic implications in 6- to 10-kg nursery pigs.

MATERIALS AND METHODS

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. The study was conducted at the Kansas State University Swine Teaching and Research Center in Manhattan, KS.

A total of 255 nursery pigs (PIC 327 × 1050, initially 6.3 ± 0.06 kg and 3-d after weaning) were used in a 28-d growth trial. Pigs were weaned at 21 d of age and placed in the nursery facility. At weaning, pigs were fed a common diet for 3 d. At d 3 after weaning, pigs were weighed and allotted to dietary treatments in a randomized complete block design blocked by BW. Therefore, d 3 after weaning was d 0 in the trial. Each treatment had 7 replications with 6 or 7 pigs per pen. A 4-hole, dry self-feeder and a nipple waterer were used in each pen (1.22 × 1.52 m) to provide ad libitum access to feed and water. A 2-phase diet series was used with treatment diets fed from d 0 to 14 and a common diet fed from d 14 to 28. Experimental diets were corn-soybean meal-based with addition of crystalline L-Trp to achieve 6 levels of SID Trp that were 14.7, 16.5, 18.4, 20.3, 22.1, and 24.0% of Lys (Table 2.1). Nutrients and SID AA digestibility values used for diet formulation were obtained from NRC (1998). Large batches of the 14.7% and 24.0% SID Trp:Lys diets were made then blended to achieve the intermediate SID Trp:Lys ratios (Table 2.2). Based on data of Nemechek et al. (2011) using the same sources of pigs in the same nursery facility, diets were formulated to 1.30% SID Lys. The 14.7% SID Trp:Lys ratio diet was also verified to be deficient in Trp (Nemechek et al., 2011). All diets in phase 1 contained 10% spray-dried whey and did not contain specialty protein sources such as spray-dried blood meal or select menhaden fishmeal. All experimental diets were fed in meal form and were prepared at the Kansas State University Animal Sciences and Industry Feed Mill.

Diet samples were collected from feeders at the beginning of the trial and on d 7 and 14. At the end of the trial, samples of each diet collected on d 0, 7, and 14 were combined and a composite sample was analyzed for AA content (Ajinomoto Heartland LLC, Chicago, IL). Weight and feed disappearance were determined at d 0, 7, 14, 21, and 28 to calculate ADG, ADFI, G:F, g of SID Trp intake per kg of gain, feed cost per kg of gain, and income over feed cost (IOFC).

The total amount of SID Trp intake was divided by total BW gain from d 0 to 14 to represent the g of SID Trp intake per kg of gain. Feed cost per kg of gain was calculated by dividing the total feed cost (Feed cost per pig, \$/pig = feed cost, \$/kg × total feed consumed (F/G × total gain, kg)) by the total BW gain per pig (ADG × days on feed). Income over feed cost is a method to measure an economic value by assuming that other costs, such as utility and labor, are constant and the only variables are ADG and feed usage. Income over feed cost was calculated by subtracting the feed cost per pig from the gross income per pig. Gross income per pig is the income from selling one pig that was calculated from the total weight gain multiplied with the pig price. In the economic calculations, the average 5-year (2008 to 2012) price of corn, soybean meal, and pig live weight reported by USDA was used. Corn was valued at \$195/tonne, soybean meal at \$384/tonne, spray-dried whey at \$847/tonne, L-Lys HCl at \$1,762/tonne, DL-Met at \$3,304/tonne, Thr at \$2,533/tonne, L-Trp at \$26,432/tonne, and pig price at \$1.20/kg live weight.

Statistical analysis

Data were analyzed for linear and quadratic effects of increasing SID Trp:Lys ratio using the PROC MIXED procedure of SAS (SAS Institute, Inc., Cary, NC). Pen was the experimental unit for all data analysis and BW block was included as a random effect. Results were considered significant at $P \leq 0.05$ and were considered a trend at $P > 0.05$ and $P \leq 0.10$. The PROC MIXED procedure of SAS was also used to develop a regression equation to predict growth dependent on SID Trp:Lys level, then the equation was used to investigate the return in growth to an incremental unit of increasing % SID Trp:Lys.

RESULTS

The analyzed total AA of experimental diet samples were within coefficient of variation between laboratory according to Cromwell et al. (1999) (Table 2.3).

From d 0 to 14, increasing SID Trp:Lys ratio improved ADG (linear, $P = 0.02$) and tended to improve ADFI (linear, $P = 0.06$) and G:F (quadratic, $P = 0.08$; Table 2.4). Although the response was linear for ADG and ADFI, and similar to G:F, performance was maximized for pigs fed the 20.3% SID Trp:Lys ratio. Increasing SID Trp:Lys ratio tended to improve feed cost per kg of gain (quadratic, $P = 0.08$), but no differences were found in IOFC. Nevertheless, pigs fed the 20.3% SID Trp:Lys ratio resulted in the lowest feed cost per kg of gain and greatest IOFC. Additionally, SID Trp intake per kg of gain increased with increasing SID Trp:Lys ratio (linear, $P < 0.01$). A value of 3.5 g SID Trp for a kg of gain was observed for pigs fed the 20.3% SID Trp:Lys ratio and had the greatest growth rate and feed efficiency.

From d 14 to 28, when a common diet was fed, ADFI increased (linear, $P = 0.05$) with increasing SID Trp:Lys ratio fed from d 0 to 14; however, no evidence of a carryover effect for ADG, G:F, and feed cost per kg of gain was observed. Pigs previously fed the 20.3% SID Trp:Lys ratio also had the lowest feed cost per kg of gain and greatest IOFC during this period.

For the overall study (d 0 to 28), ADG and ADFI increased ($P > 0.03$) with increasing SID Trp:Lys ratio, but no differences were detected for G:F, feed cost per kg of gain or IOFC. Although ADG and ADFI were linear in response, little benefit was gained in performance above the 20.3% SID Trp:Lys ratio and pigs fed the 20.3% SID Trp:Lys ratio had the lowest feed cost per kg of gain and greatest IOFC.

DISCUSSION

The best G:F and ADG were both observed at 20.3% SID Trp:Lys, thus suggesting this ratio was optimum to maximize growth performance. This ratio was greater than the value of 16.3 and 16.8% that were extrapolated from the recommended SID Lys and Trp from NRC (2012) and the National Swine Nutrition Guide (2010) for similar BW range. Likewise, the meta-analysis by Simongiovanni et al. (2012) concluded a lower SID Trp:Lys requirement (17%) for 7- to 25-kg pigs when using linear-plateau model, whereas, a 22 and 26% SID Trp:Lys were estimated from curvilinear-plateau and asymptotic model, respectively. In addition, Guzik et al. (2005) summarized at least 19.5% SID Trp:Lys ratio for 7- to 16-kg nursery pigs fed with pea-barley-wheat diet.

In this study, the quadratic improvement in G:F with increasing Trp suggested a diminishing of return in G:F as SID Trp:Lys ratio increased. Thus, the regression analysis was performed to generate the equation describing the quadratic relationship between G:F and SID Trp:Lys ratio in the study [G:F =(0.06755 × % SID Trp:Lys^2) + (- 0.00163× % SID Trp:Lys) + 0.04595]. The first derivative of this equation was then used to describe an incremental response in G:F to an incremental unit of increasing % SID Trp:Lys or the marginal efficiency. The marginal efficiency curve illustrated a diminishing of return in G:F as SID Trp:Lys ratio increased and then reached zero at 20.3% SID Trp:Lys where the maximum G:F was observed (Figure 2.1). The negative marginal efficiency beyond 20.3% SID Trp:Lys ratio showed a reduction in G:F after a maximum was reached. The diminishing return to increasing Trp as the maximum response is approached in this study is similar to the response for increasing Lys (Gahl et al., 1994). The economic evaluation is therefore important to determine the optimal dietary Trp level to achieve maximum profit. In this study, IOFC was not statistically different; however, the value change when comparing across treatments is substantial. Feeding a 20.3% SID Trp:Lys ratio resulted in the best IOFC which was correlated to the best performance. Only a minimal reduction (5%) in IOFC was observed when feeding up to 22.1% due to feed cost whereas growth and feed efficiency were maintained. However, the increased feed intake and feed cost but lack of further weight gain when feeding up to 24% SID Trp:Lys resulted in a 12% reduction in IOFC compared to feeding Trp at 20.3% of Lys. Similarly, a 13 to 15% reduction from the maximal IOFC at 20.3% was demonstrated for feeding with 18.4 and 16.5% SID Trp:Lys as a result of poorer growth rate and feed efficiency. Feeding 14.7% SID Trp:Lys ratio resulted in a 20% loss in IOFC compared with feeding 20.3% SID Trp:Lys due to the detrimental effect of Trp deficiency on feed intake and the subsequent growth performance.

Revenue in the IOFC calculation was a function of growth and pig price whereas total feed cost was dictated by efficiency to convert feed to growth and the diet cost. Therefore, the IOFC can change over time as the prices of pig and feed ingredients alter. In this study, the SID Trp:Lys ratio was increased by adding the crystalline L-Trp in expense of corn starch. The difference in feed cost per tonne between diets was therefore dependent on the amount and price of crystalline L-Trp. In the previous IOFC calculation with using the 5-year average price of corn, soybean meal, and pig price, the price of crystalline L-Trp was fixed at $26,432/tonne. However, when price of crystalline L-Trp changes to $13,216 (-50%) and 39,648 (+50%)/tonne, the result was similar where IOFC was greatest at 20.3% SID Trp:Lys ratio with a small reduction (5 to 7%) in IOFC from the maximum at 22% SID Trp:Lys (Figure 2.2). Lowering SID Trp:Lys to 14.7% greatly reduced the IOFC from the maximum by 19 to 23%.

Corn and soybean meal were the main ingredients (58 and 25% of the diet) in the diet and contributed 40 to 45% of the total cost of each diet. Thus, the average yearly price of corn ($148 to 253/tonne) and soybean meal ($343 to 477/tonne) reported by USDA from 2008 to 2012 were used to calculate IOFC whereas price of other ingredients including pig price were held constant to examine the effect of increasing SID Trp:Lys ratio on economic return over 5-year period (Figure 2.3). Similar to using the 5-year average price of corn and soybean meal, feeding 20.3% SID Trp:Lys resulted in the best IOFC across the 5 year period. Increasing SID Trp:Lys ratio to 22.1% resulted in a small reduction in IOFC of 5 to 6% comparing to the maximum IOFC at 20.3% SID Trp:Lys ratio. Feeding 24% SID Trp:Lys led to 14 to 17% reduction in IOFC from the maximum. Lowering SID Trp:Lys to 18.4 and 16.5% reduced IOFC by 11 to 15% from the maximum IOFC at 20.3% SID Trp:Lys whereas feeding 14.7% SID Trp:Lys showed a severe reduction in IOFC as great as 23%.

The variation in market pig price was another variable to impact IOFC. Therefore, the lowest ($0.82/kg), highest ($1.67/kg), and average ($1.20/kg) pig prices during 2008 to 2012 reported by USDA were used in IOFC calculation whereas diet cost was held constant (Figure 2.4). Across all pig prices, the greatest IOFC was observed at 20.3% SID Trp:Lys. Increasing SID Trp:Lys to 22.1% resulted in only a small reduction (5 to 11%) in IOFC comparing to the maximum IOFC at 20.3% SID Trp:Lys across all pig prices. Feeding 24% SID Trp:Lys reduced IOFC from the maximum by 10 to 15% at the highest and average pig price and as much as a 40% reduction when pig price was lowest in the period. Similarly, feeding at 16.5 and 18.4% SID Trp:Lys showed 11 to 15% lower IOFC comparing to feeding at 20.3% SID Trp:Lys when pig price was high or at average; however, as great as 25% lower IOFC from maximum when at the lowest pig price. Also, lowering SID Trp to 14.7% of Lys reduced IOFC (18 to 37%) compared with the maximum IOFC at 20.3% across all pig prices.

It is apparent from the IOFC evaluations that feeding 20.3% SID Trp:Lys provided the best growth performance and benefit in all scenarios. Increasing SID the Trp:Lys ratio to 22.1% minimally affected growth rate and feed efficiency such that IOFC was reduced by only a small extent comparing to feeding at 20.3%. However, lowering the SID Trp:Lys ratio below 20.3% negatively impacted growth performance such that a lower diet cost from lower crystalline L-Trp addition to the diets could not overcome, especially when feeding at 14.7% SID Trp:Lys that the markedly reduction in feed intake negatively affected growth.

The amount of SID Trp for a kg of gain at the maximum growth was observed at 3.5 g in this study. This amount is close to the requirement estimates of 3.2 g SID Trp/kg gain in Guzik et al. (2002) study but significantly higher than the values (2.5 to 2.7 g SID Trp/kg gain) estimated from data by Burgoon et al. (1992), Cadogan et al. (1999), and Eder et al. (2001) reported in NRC (2012) for pigs at a similar BW.

In conclusion, the diminishing return of feeding Trp that was observed in our study stresses the importance of determining the response in monetary units. The economics of feeding different levels of Trp depends on feed cost and value the weight gain which is unique in each circumstance; therefore, the economic evaluation should be investigated at the time of use to be more accurate. Based on our results, we concluded the optimal SID Trp:Lys ratio for 6-to 10-kg nursery pigs to be 20.3% with feeding up to 22.1% neither decreasing growth performances or economic return. The 22.1% ratio is higher than is current standard of practice by nutritionists in the US and that suggested by NRC (2012).

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FIGURES AND TABLES

Table 2.1 Diet composition (as-fed basis)[1]

Item	Treatment diet	Common diet[2]
Ingredient, %		
Corn	58.10	65.05
Soybean meal (46.5% CP)	25.20	30.73
Spray-dried whey	10.00	---
Soybean oil	1.00	---
Monocalcium P (21% P)	1.10	1.08
Limestone	0.90	0.95
Salt	0.35	0.35
Zinc oxide	0.25	---
Trace mineral premix[3]	0.15	0.15
Vitamin premix[4]	0.25	0.25
L-Lys HCl	0.533	0.360
DL-Met	0.220	0.130
L-Thr	0.230	0.130
L-Ile	0.100	---
L-Val	0.160	---
Gln	0.630	---
Gly	0.630	---
Phytase[5]	0.085	0.165
Corn starch	---	---
L-Trp	---	---
TOTAL	100	100
Calculated analysis		
Standadized ileal digestible (SID) amino acids %		
Lys	1.30	1.26
Ile:Lys	60	61
Leu:Lys	111	129
Met:Lys	36	33
Met & Cys:Lys	58	58
Thr:Lys	64	63
Trp:Lys	14.7[6]	17.0
Val:Lys	70	68
Total Lys, %	1.42	1.39
ME, kcal/kg	3,341	3,311
SID Lys:ME, g/Mcal	3.89	3.80
CP, %	20.4	20.8
Ca, %	0.72	0.69
P, %	0.64	0.62
Available P, %	0.47	0.42

[1] Treatment diets were fed from d 0 to 14.
[2] Common diet was fed from d 14 to 28.
[3] Provided per kg of premix: 26.5 g Mn from manganese oxide, 110 g Fe from iron sulfate, 110 g Zn from zinc sulphate, 11 g Cu from copper sulfate, 198 mg I from calcium iodate, and 198 mg Se from sodium selenite.
[4] Provided per kg of premix: 4,409,200 IU vitamin A; 551,150 IU vitamin D3; 17,637 IU vitamin E; 1,764 mg vitamin K; 3,307 mg riboflavin; 11,023 mg pantothenic acid; 19,841 mg niacin; and 15.4 mg vitamin B12.
[5] Phyzyme 600 (Danisco Animal Nutrition, St. Louis, MO) provided 509 FTU/kg, with a release of 0.10% available P.
[6] Crystalline L-Trp was added at the expense of corn starch at 0, 0.024, 0.049, 0.074, 0.098, and 0.123% of the diet to provide Trp:Lys ratios of 1.47, 16.5, 18.4, 20.3, 22.1, and 24.0%.

Table 2.2 Percentage of high and low SID Trp:Lys blended to create the treatment diets

	Basal diets	
SID Trp:Lys	Low SID Trp:Lys (14.7%)	High SID Trp:Lys (24.0%)
14.7%	100%	0%
16.5%	80%	20%
18.4%	60%	40%
20.3%	40%	60%
22.1%	20%	80%
24.0%	0%	100%

Table 2.3 Total AA analysis (as-fed-basis)[1]

	Standardized ileal digestible Trp:Lys ratio, %					
Item	14.7	16.5	18.4	20.3	22.1	24.0
Lys	1.43 (1.42)[2]	1.43 (1.42)	1.42 (1.42)	1.38 (1.42)	1.37 (1.42)	1.42 (1.42)
Ile	0.90 (0.87)	0.95 (0.87)	0.93 (0.87)	0.94 (0.87)	0.91 (0.87)	0.93 (0.87)
Leu	1.61 (1.61)	1.63 (1.61)	1.60 (1.61)	1.60 (1.61)	1.53 (1.61)	1.60 (1.61)
Met	0.50 (0.50)	0.46 (0.50)	0.49 (0.50)	0.47 (0.50)	0.49 (0.50)	0.49 (0.50)
Cys	0.32 (0.32)	0.32 (0.32)	0.32 (0.32)	0.31 (0.32)	0.31 (0.32)	0.32 (0.32)
Thr	0.95 (0.93)	0.97 (0.93)	0.95 (0.93)	0.94 (0.93)	0.94 (0.93)	0.95 (0.93)
Trp	0.22 (0.22)	0.23 (0.24)	0.24 (0.26)	0.27 (0.29)	0.30 (0.31)	0.30 (0.34)
Val	1.07 (1.02)	1.05 (1.02)	1.04 (1.02)	1.05 (1.02)	1.03 (1.02)	1.05 (1.02)

[1] Diet samples were collected from feeder at the beginning of the trial and on d 7 and 14. At the end of the trial, samples of each diet collected on d 0, 7, and 14 were combined and a composite sample was analyzed for total AA analysis by Ajinomoto Heartland LLC (Chicago, IL).

[2] Values in parentheses indicate formulated values.

Table 2.4 Influence of standardized ileal digestible (SID) Trp:Lys ratio on growth performance of nursery pigs[1]

	SID Trp:Lys, %							Probability, *P* <	
	14.7	16.5	18.4	20.3	22.1	24.0	SEM	Linear	Quadratic
d 0 to 14									
ADG, g	226	244	244	266	258	260	11.7	0.02	0.33
ADFI, g	325	342	342	349	341	363	11.6	0.06	0.94
G:F	0.694	0.713	0.713	0.762	0.755	0.717	0.039	0.06	0.08
d 14 to 28									
ADG, g	487	468	489	504	482	501	11.7	0.18	0.88
ADFI, g	710	696	735	733	712	754	16.2	0.05	0.78
G:F	0.685	0.672	0.666	0.688	0.679	0.666	0.015	0.66	0.90
d 0 to 28									
ADG, g	356	356	365	385	370	380	8.9	0.02	0.60
ADFI, g	518	519	537	541	526	558	12.1	0.03	0.86
G:F	0.689	0.685	0.681	0.713	0.704	0.682	0.012	0.59	0.33
BW, kg									
d 0	6.3	6.3	6.2	6.3	6.2	6.3	0.06	0.75	0.87
d 14	9.4	9.7	9.7	10.0	9.9	9.9	0.18	0.03	0.29
d 28	16.2	16.2	16.5	17.0	16.6	16.9	0.25	0.03	0.53
Feed cost/kg gain[2], $									
d 0 to 14	0.69	0.67	0.68	0.65	0.66	0.71	0.02	0.95	0.08
d 14 to 28	0.41	0.41	0.42	0.40	0.41	0.42	0.01	0.65	0.92
d 0 to 28	0.49	0.50	0.51	0.49	0.50	0.52	0.01	0.21	0.35
IOFC[3], $/pig									
d 0 to 14	1.69	1.84	1.80	2.11	2.00	1.85	0.14	0.17	0.17
d 14 to 28	5.50	5.24	5.45	5.70	5.42	5.57	0.17	0.41	0.95
d 0 to 28	7.18	7.08	7.22	7.81	7.42	7.41	0.22	0.15	0.43
SID Trp g/kg gain[4]	2.8	3.0	3.4	3.5	3.8	4.4	0.09	0.01	0.06

[1]A total of 255 nursery pigs (PIC 327 × 1050, initially 6.3 kg and 3-d postweaning) were used in a 28-d trial with 6 to 7 pigs per pen and 7 pens per treatment. Experimental diets were fed from d 0 to 14, and common diet was fed from d 14 to 28.

[2] Feed cost per kg of gain was calculated by dividing the total feed cost (Feed cost per pig, $/pig = feed cost, $/kg × total feed consumed (F/G × total gain, kg)) by the total BW gain per pig (ADG × days on feed). Corn was valued at $195/tonne, soybean meal at $384/tonne, spray-dried whey at $847/tonne, L-Lys HCl at $1,762/tonne, DL-Met at $3,304/tonne, L-Thr at $2,533/tonne, L-Trp at $26,432/tonne, and pig price at $1.20/kg in feed cost per kg of gain and income over feed cost calculations.

[3]Income over feed cost was calculated by subtracting the feed cost per from the gross income per pig.

[4]Calculated % SID Trp in diet was used in the calculation of gram of SID Trp intake per kg of BW gain from d 0 to 14.

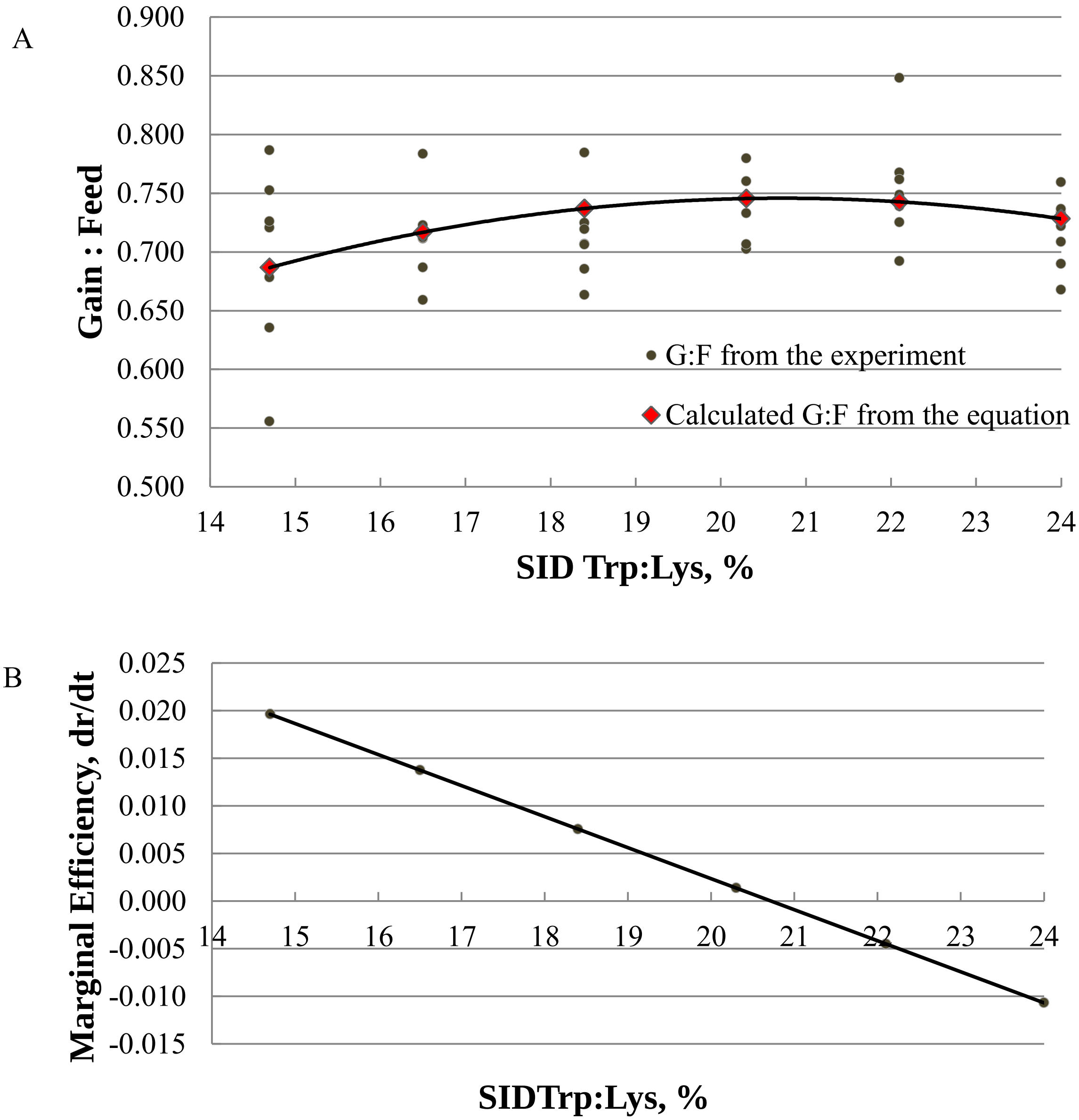

Figure 2.1 Relationship between G:F and SID Trp:Lys and marginal efficiency

A) The quadratic relationship between G:F and SID Trp:Lys in the study generated from regression analysis [G:F = (- 0.00163× % SID Trp:Lys) + (0.06755 × % SID Trp:Lys^2) + 0.04595]. Circle point represents G:F response of each experimental unit (pen).

B) The first derivative of the equation was used to describe an incremental response in G:F to an incremental unit of increasing %SID Trp:Lys or the marginal efficiency. The marginal efficiency curve illustrated a diminishing of return in G:F as % SID Trp:Lys increased and then reached zero at 20.3% SID Trp:Lys where the maximum G:F was observed.

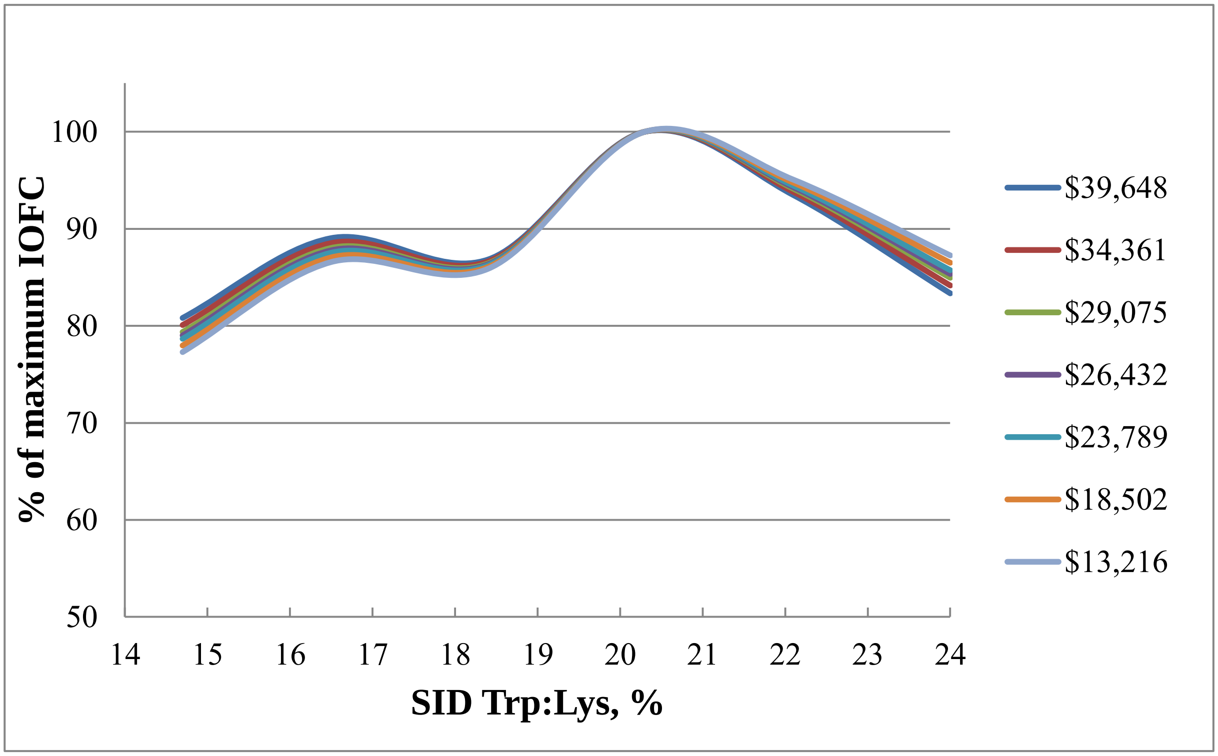

Figure 2.2 Income over feed cost of feeding SID Trp:Lys with changing price of crystalline L-Trp

Price of crystalline L-Trp from $13,216 to 39,648/tonne were used to calculate IOFC whereas other ingredient prices (Corn was valued at $195/tonne, soybean meal at $384/tonne, spray-dried whey at $847/tonne, L-Lys HCl at $1,762/tonne, DL-Met at $3,304/tonne, L-Thr at $2,533/tonne) and pig price ($1.20/kg) were constant to examine the effect of increasing SID Trp:Lys on economic return.

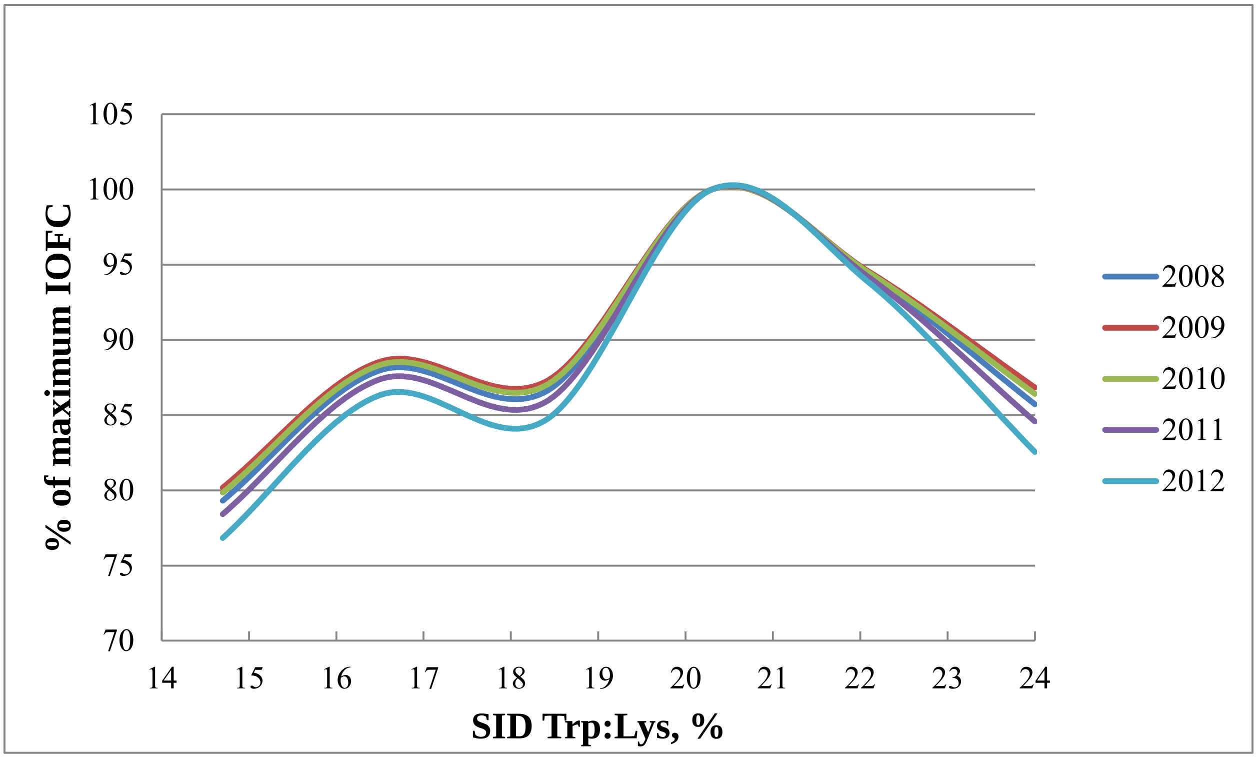

Figure 2.3 Income over feed cost of feeding SID Trp:Lys using corn and soybean meal prices from 2008 to 2012 (USDA).

Average yearly price of corn ($148 to 253/tonne) and soybean meal ($343 to 477 /tonne) reported by USDA from 2008 to 2012 were used to calculate IOFC whereas other ingredient prices and pig price were held constant to examine the effect of increasing SID Trp:Lys on economic return over the 5-year period.

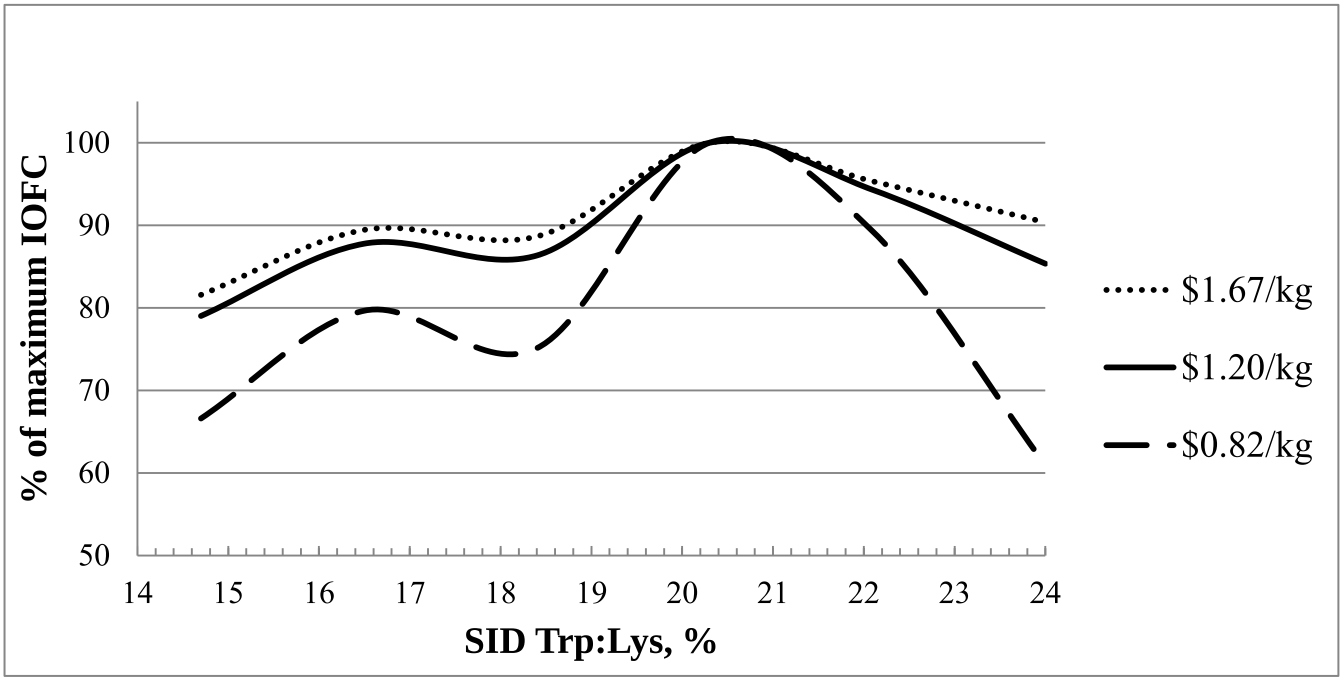

Figure 2.4 Income over feed cost of feeding SID Trp:Lys at different pig prices.

The lowest ($0.82/kg), highest ($1.67/kg), and average ($1.20/kg) pig prices during 2008 to 2012 reported by USDA were used in IOFC calculation whereas diet cost was held constant.

Chapter 3 - The Effects of Standardized Ileal Digestible Tryptophan:Lysine Ratio in Diets Containing Dried Distillers Grains with Solubles on Growth Performance and Carcass Characteristics of Finishing Pigs

ABSTRACT

Three studies were conducted to investigate the effects of increasing standardized ileal digestible (SID) Trp:Lys ratio on growth performance and carcass characteristics of finishing pigs fed with diets containing high inclusion rate of dried distiller grains with solubles (DDGS). In Exp.1, 845 pigs (initially 74 kg BW) were used in a 61-d trial (6 pens per treatment). Treatments were DDGS diets with 4 SID Trp:Lys ratios (15, 17, 19, and 21%) using crystalline L-Trp to increase the Trp level. An additional treatment diet contained a SID Trp:Lys ratio of 21% where soybean meal was used as the source of Trp. No effect ($P > 0.25$) on growth performance was observed with increasing SID Trp:Lys. Pigs fed diet containing 21% SID Trp:Lys ratio from crystalline L-Trp had better G:F ($P = 0.01$) than pigs fed the diet with increased soybean meal. In Exp. 2, 2,298 pigs (initially 71 kg BW) were used in a 52-d study (8 to 9 pens per treatment). Treatments were arranged as a 2 × 6 factorial with main effects of gender (gilts or barrows) and SID Trp:Lys ratio (2 positive control diets with no DDGS containing SID Trp:Lys ratios of 17 or 21% and 4 diets containing 30% DDGS with SID Trp:Lys ratios of 15, 17, 19, or 21%). No gender × treatment interactions were observed. Increasing SID Trp:Lys ratio from 15 to 21% in diets containing 30% DDGS had no effect on ADG, ADFI, or G:F but increased (linear, $P < 0.01$) percentage carcass yield. In Exp.3, 1,235 pigs (initially 68 kg BW) were used in a 71-d study with 7 to 8 pens per treatment. Treatments were arranged as a 2 ×

3 factorial with main effects of SID Trp:Lys ratio (16.5 or 20%) and DDGS (0, 20, or 40%). No differences were observed in growth performance due to SID Trp:Lys ratio. Increasing DDGS resulted in poorer G:F (linear, $P = 0.02$), but did not influence other growth performance responses. For carcass characteristics, increasing the SID Trp:Lys ratio increased ($P = 0.02$) percentage carcass yield with the greatest improvement observed at high levels of DDGS (20 and 40%) (Trp × DDGS interaction, $P = 0.07$). A tendency for a Trp × DDGS interaction (linear, $P = 0.08$) was observed for lean percentage, with lean percentage decreasing as DDGS increased in diets containing the 16.5% SID Trp:Lys ratio and no change in lean percentage as DDGS increased in diets containing the 20% SID Trp:Lys ratio. Our results suggest that percentage carcass yield and lean increase with increasing SID Trp:Lys in late finishing pigs that are fed high levels of DDGS.

Key words: Dried distillers grains with solubles, finishing pig, lysine, tryptophan

INTRODUCTION

It is well documented that the large neutral amino acids (LNAA) which includes branched-chain amino acids (Ile, Leu, and Val) and aromatic amino acids (Phe and Tyr) share a common transport system with Trp resulting in competitive absorption at the intestine and blood-brain barrier (Henry and Seve, 1993). Thus, it is hypothesized that the high level of LNAA in the diet will elevate the requirement for Trp as a decreased amount of Trp from the diet is absorbed. A high LNAA concentration in diet has been reported to decrease growth performance at both adequate and sub-optimal Trp levels, with a large decrease observed at the low level of Trp (Henry, 1995; Henry et al., 1996). Because corn protein is relatively low in Trp and high in LNAA, the concentrations of LNAA increases as corn byproducts, such as DDGS, increases in the diet. Accordingly, the interaction between LNAA and Trp raises the concern regarding the optimal Trp level in diets with high levels of DDGS.

Currently, there are only a few studies reported on the Trp requirement in diets containing DDGS in grower-finisher. Hinson et al. (2010) found a 16% standardized ileal digestible (SID) Trp:Lys ratio to be optimum for 27- to 117-kg pigs. This agrees with the finding of Salyer et al. (2013) that indicated a 16.5% SID Trp:Lys ratio requirement for 36- to 70-kg pigs fed with diets containing 30% DDGS. Nevertheless, a greater than 19.5% SID Trp:Lys ratio was estimated for the late finishing period (> 70 kg BW) in the same study. Apparently, the Trp requirement in diets with high levels of DDGS is variable and needs to be further investigated.

Therefore, three studies were conducted to investigate the influence of increasing SID Trp:Lys ratio on growth performance and carcass characteristics of finishing pigs fed with high levels of DDGS.

MATERIALS AND METHODS

All experimental procedures and animal care were approved by the Kansas State University Institutional Animal Care and Use Committee. All three studies were conducted off-campus at commercial research-finishing barns.

Experiment 1

A total of 845 pigs (PIC 380 × Monsanto) with an initial BW of 74 kg were used in a 61-d study. A similar number of barrows and gilts were placed in each pen with 25 to 30 pigs per pen and the average number of pigs per pen similar across treatments. There were 6 pens per treatment. Pigs were fed a pretest diet containing 35% DDGS before the start of the experiment

(Table 3.1). When pigs reached 74 kg BW, pens of pigs were allotted to 1 of the 5 dietary treatments in a completely randomized design while balancing for initial BW.

Treatments were diets with 4 SID Trp:Lys ratios (15, 17, 19, and 21%) using crystalline L-Trp additions. An additional treatment diet contained a SID Trp:Lys ratio of 21% where soybean meal was used as the source of Trp. The total amino acid content along and standardized ileal digestibility coefficients were obtained from NRC (1998) for corn and soybean meal and Stein (2007) for DDGS and used in diet formulation. All diets were fed in meal form and fed in 3 phases from d 0 to 21 (74 to 95 kg BW), d 21 to 42 (95 to 113 kg BW), and d 42 to 61 (113 to 130 kg BW; Tables 3.1 and 3.2). All diets contained 30% DDGS except diets fed in the last phase, in which DDGS level was lowered to 15% to reduce the negative impact on carcass fat quality and carcass yield. Diets in phase 3 also contained 7.5 ppm of Ractopamine HCl (Paylean; Elanco Animal Health, Greenfield, IN). Diet samples from each phase were collected and analyzed for total AA by Ajinomoto Heartland LLC (Chicago, IL). Daily feed additions to each pen were accomplished through a robotic feeding system (FeedPro; Feedlogic Corp., Willmar, MN) capable of providing and measuring feed amounts for individual pens. Pens of pigs were weighed and feed disappearance was recorded at d 10, 21, 31, 42, and 61 to determine ADG, ADFI, and G:F. On d 42 of the experiment, the 4 heaviest pigs (2 barrows and 2 gilts determined visually) per pen were weighed and sold according to the farm’s normal marketing procedure. The formulated SID Trp in each phase was used to calculate g of SID Trp intake by phase then the summation of SID Trp intake of all phases was divided with the overall BW gain to represent the g of SID Trp intake per kg of BW gain.

Experiment 2

A total of 2,298 pigs (half gilts and half barrows, PIC TR4 × 1050) with an initial BW of 71.4 kg were used in a 52-d study; each pen contained 23 pigs and each treatment comprised 8 to 9 pens. Pens of pigs were allotted to 1 of 6 dietary treatments in a completely randomized design within gender while balancing for initial BW. Treatments were arranged as a 2 × 6 factorial with main effects of gender (gilts or barrows) and SID Trp:Lys ratio (2 positive control diets with no DDGS containing SID Trp:Lys ratios of 17 or 21% and 4 diets contained 30% DDGS with SID Trp:Lys ratios of 15, 17, 19, or 21%). Soybean meal replaced corn, L-Lys HCl, and L-Thr to increase the SID Trp:Lys ratios from 15 to 21% (Tables 3.3 to 3.5). Large batches of the 15% and 21% SID Trp:Lys diets were made then blended on farm to achieve the intermediate SID Trp:Lys ratios. All diets were fed in meal form and treatments were fed in 3 phases, d 0 to 21 (71.4 to 95 kg BW), d 21 to 42 (95 to 113 kg BW), and d 42 to 52 (113 to 125 kg BW; Tables 3.3 to 3.5). During the last phase, the DDGS level was lowered to 20%. Diet samples from each phase were collected and analyzed for total AA by Ajinomoto Heartland LLC (Chicago, IL) and Evonik Degussa Corporation (Kennesaw, GA).

Pigs were housed in double-curtain-sided barns. Pens had completely slatted flooring and shallow pits for manure storage. Each pen was equipped with a 4-hole stainless steel dry self-feeder and a swinging nipple waterer for ad libitum access to feed and water. Daily feed additions to each pen were accomplished through an automated feeding system capable of providing and measuring feed amounts for individual pens.

Pens of pigs were weighed and feed disappearance was recorded at d 21, 42, and 52 to determine ADG, ADFI, and G:F. The formulated SID Trp in each phase was used to calculate g of SID Trp intake by phase then the summation of SID Trp intake of all phases was divided with the overall BW gain to represent the g of SID Trp intake per kg of BW gain. At the end of the experiment, pigs were individually tattooed by pen number to allow for carcass data collection at the packing plant and data retrieval by pen. Pigs were transported to Triumph Foods LLC (St. Joseph, MO) for processing. Standard carcass criteria of loin and backfat depth, HCW, percentage lean, and percentage carcass yield were collected. Percentage of yield was calculated by dividing carcass weight at the plant with live weight at the plant as reported by the processor.

Experiment 3

A total of 1,235 pigs (PIC 1050 × 337) with an initial BW of 68 kg were used in a 71-d study. A similar number of barrows and gilts were placed in each pen, with 26 to 28 pigs per pen and 7 to 8 pens per treatment. Pens of pigs were allotted to 1 of 6 dietary treatments in a completely randomized design while balancing for BW. Treatments were arranged as a 2 × 3 factorial with main effects of SID Trp:Lys ratio (16.5 or 20% of lysine) and DDGS (0, 20, or 40%). Pigs were fed a common diet containing a 17.3% SID Trp:Lys ratio from approximately 45 to 68 kg BW (Table 3.6). Dried distillers grains with solubles and Lys sulfate were added at the expense of corn and soybean meal to increase the DDGS level in the diet while maintaining the SID Trp:Lys ratio at 16.5%. Soybean meal replaced Corn, L-Lys HCl, and L-Thr to increase the SID Trp:Lys ratio from 16.5 to 20%. The amino acid contents along with standardized digestibility coefficients from NRC (1998) for corn, soybean meal, and Stein (2007) for DDGS were used in diet formulation. All diets were fed in meal form and treatments were fed in 3 phases from 68 to 89 kg, 89 to 109 kg, and 109 to 137 kg BW (Tables 3.6 to 3.8). In the last phase, DDGS levels for the 20 and 40% diets were lowered to 10 and 20%, respectively, to reduce the negative impact on carcass fat quality and carcass yield. Phase 3 diets also contained 10 ppm of Ractopamine HCl (Paylean; Elanco Animal Health, Greenfield, IN).

Pigs were housed in naturally ventilated and double-curtain-sided barns. Pens had completely slatted flooring and deep pits for manure storage. Each pen was equipped with a 5-hole stainless steel dry self-feeder and a cup waterer for ad libitum access to feed and water. Daily feed additions to each pen were accomplished through a robotic feeding system (FeedPro; Feedlogic Corp., Willmar, MN) capable of providing and measuring feed amounts for individual pens.

Pens of pigs were weighed and feed disappearance was recorded at d 22, 44, and 71 to determine ADG, ADFI, and G:F. The formulated SID Trp in each phase was used to calculate g of SID Trp intake by phase then the summation of SID Trp intake of all phases was divided with the overall BW gain to represent the g of SID Trp intake per kg of BW gain. On d 44 of the experiment, the 4 heaviest pigs (2 barrows and 2 gilts, determined visually) per pen were weighed and sold according to the farm's normal marketing procedure. At the end of the trial (d 71), pigs were individually tattooed by pen number to allow for carcass data collection. Pigs were transported to JBS Swift and Company (Worthington, MN) for processing and carcass data collection. Hot carcass weights were measured immediately after evisceration, and standard carcass criteria of percentage carcass yield, carcass weight, percentage lean, backfat depth, and loin depth were collected. Percentage carcass yield was calculated by dividing carcass weight at the plant with live weight at the plant as reported by the processor.

Statistical Analysis

Pen was the experimental unit for all data and analyzed using the MIXED procedure of SAS (SAS institute, Inc., Cary, NC) in Exp. 1 and 3 and the GLM procedure was used in the analysis in Exp.2. Differences were considered significant with $P \leq 0.05$ and trends if $P > 0.05$

and ≤ 0.10. Analysis of backfat depth, loin depth, and percentage lean were adjusted to a common carcass weight using HCW as a covariate. In Exp.1, data were analyzed for the linear and quadratic effects of increasing SID Trp:Lys ratio using contrasts. Also, a single contrast was used to compare the 2 diets with SID Trp:Lys ratios of 21% from either crystalline L-Trp or soybean meal. In Exp. 2, the main effect of DDGS level was analyzed by comparing the corn-soybean meal diets containing 17 and 21% SID Trp:Lys ratio with the 30% DDGS diets containing 17 and 21% SID Trp:Lys ratio. Data also were analyzed to determine the influence of increasing SID Trp:Lys ratio in diets without DDGS (17 vs. 21% SID Trp:Lys ratio), linear and quadratic effect of increasing SID Trp:Lys ratio (15, 17, 19, or 21%) in diet containing 30% DDGS, and any interactions between tryptophan level and gender. In Exp. 3, data were analyzed for the main effects of SID Trp:Lys ratio, linear and quadratic effect of DDGS, and interaction between SID Trp:Lys ratio and DDGS using contrasts.

RESULTS

Diet Analysis

The analyzed AA were within coefficient of variation between laboratories according to Cromwell et al. (1999) and within analytical variation for Lys content according to AAFCO (2013) except for the total Trp content of the 15% SID Trp:Lys ratio 30% DDGS diet in phase 1 and 2 of Exp.2 that was higher (20%) than formulated. Diet samples collected for Exp. 3 were not available analysis.

Experiment 1

Overall (d 0 to 61), increasing SID Trp:Lys ratio had no effect ($P > 0.25$) on growth performance but increased g of SID Trp intake per kg of BW gain (linear, $P < 0.01$; Table 3.13).

Pigs fed diet containing 21% SID Trp:Lys ratio from crystalline L-Trp had greater (P = 0.01) G:F and lower (P = 0.01) g of SID Trp intake per kg of BW gain than pigs fed the diet with increased soybean meal as the source of Trp.

Experiment 2

Overall from d 0 to 52, no gender × treatment interactions were observed. Pigs fed 30% DDGS had poorer ADG, ADFI, and G:F (P < 0.01, P = 0.04, and P = 0.01, respectively; Table 3.14) compared with those fed the corn-soybean meal diet. In pigs fed diets without DDGS, those fed the 17% SID Trp:Lys ratio tended to have greater G:F (P = 0.09) compared with pigs fed 21% SID Trp:Lys ratio. Increasing SID Trp:Lys ratio from 15 to 21% in diets containing 30% DDGS had no effect (P > 0.26) on ADG, ADFI, or G:F.

For carcass characteristics, feeding 30% DDGS reduced HCW, loin depth, and lean percentage (P < 0.01, P < 0.01, and P = 0.04, respectively; Table 3.14). When considering carcass traits of pigs fed corn-soybean meal diets, pigs fed 21% SID Trp:Lys ratio had decreased backfat depth (P = 0.04) resulting in greater lean percentage (P = 0.04) compared to pigs fed the 17% SID Trp:Lys ratio. Increasing the SID Trp:Lys ratio from 15 to 21% in the 30% DDGS diets had a tendency (linear, P = 0.07) to increase HCW and increased (linear, P < 0.01) percentage carcass yield.

Experiment 3

Overall (d 0 to 71), no differences were observed in growth performance between pigs fed a SID Trp:Lys ratio of either 16.5 or 20% of lysine (Table 3.15). Increasing DDGS resulted in decreased G:F (linear, P = 0.02) but did not influence the other growth performance criteria. A tendency (linear, P = 0.07) for an interaction was observed for ADFI with the greatest ADFI at 40% DDGS for 16.5% SID Trp:Lys ratio and at 20% DDGS for 20% SID Trp:Lys ratio.

Additionally, g of SID Trp intake per kg of gain was greater (*P* = 0.01) in pigs fed 20% SID Trp:Lys than those fed with 16.5% and increased with increasing SID Trp:Lys ratio (linear, *P* = 0.03).

For carcass characteristics, increasing the SID Trp:Lys ratio increased (*P* = 0.02) carcass yield with the greatest improvement in carcass yield observed when diets contained high levels of DDGS (SID Trp:Lys ratio × DDGS interaction, *P* = 0.07), but other carcass characteristics were not affected by increasing the SID Trp:Lys ratio. Pigs fed high levels of DDGS had reduced loin depth (linear, *P* = 0.02); however, the lowest loin depth was for pigs fed 40% DDGS and 16.5% SID Trp:Lys and at 20% DDGS with 20% SID Trp:Lys, resulting in a SID Trp:Lys ratio × DDGS interaction (quadratic, *P* = 0.02). A tendency for a SID Trp:Lys ratio × DDGS interaction (linear, *P* = 0.08) was observed for lean percentage, with lean percentage decreasing as DDGS were added to diets containing 16.5% SID Trp:Lys; no changes in lean percentage occurred as DDGS were added to diets containing 20% SID Trp:Lys ratio. Other carcass values were not influenced by SID Trp:Lys ratio or DDGS.

DISCUSSION

Tryptophan has been known to play a role in feed intake regulation through the appetite mediators including serotonin, insulin, and ghrelin (Le Floc'h and Seve, 2007; Zhang et al., 2007). Feeding Trp-deficient diets has clearly been shown to depress feed intake and the subsequent growth rate in nursery and finisher pigs but the feed intake and growth performances can be restored by providing the diet with adequate Trp (Guzik et al., 2002; Susenbeth and Lucanus, 2005; Jansman et al., 2010). The depressive effect was also found to be enhanced by increasing the dietary protein levels that correspond to a greater supply of the competitor amino acids (LNAA; Ile, Leu, Val, Phe, and Tyr). This limits Trp availability as they share the same transport system (Burgoon et al., 1992; Henry et al., 1992, 1996). However, in the current studies, pigs fed with the lowest Trp level had feed intake and growth rate similar to pigs fed higher Trp diets, which was unexpected because of the high dietary protein level from inclusion of DDGS. The g SID Trp per kg of gain in all 3 experiments (3.9 to 5.8 g) were also significantly higher than the values (3.4 to 3.5 g) estimated in Eder et al. (2003) and Guzik et al. (2005) for studies reported in NRC (2012) for pigs at similar BW. These observations suggest that the lowest Trp level was not deficient and might already be over the requirement, which may explain the lack of growth response with increasing Trp in our studies.

Only a few experiments have investigated the effect of increasing dietary Trp on carcass characteristics. In our studies, the tendency of interactions for carcass yield and percentage lean observed in Exp. 3 indicated an advantage to increasing the SID Trp:Lys ratio in diets with high levels of DDGS compared with no advantage to increasing the ratio in the corn-soybean meal diet. The result in Exp. 2 that found a linear improvement in carcass yield with increasing SID Trp:Lys ratio in DDGS containing diets also agreed with the result in Exp. 3. Conversely, a greater percentage lean was only observed with increasing SID Trp:Lys ratio in corn-soybean meal diets. The improvement in carcass characteristics with increasing Trp has also been demonstrated by other studies. Nitikanchana et al. (2013) increased SID Trp:Lys ratio from 16 to 20% in 30% DDGS diets and observed a linear and quadratic improvement in carcass yield when using crystalline L-Trp and soybean meal as a source of Trp, respectively. Salyer et al. (2013) found a tendency of an improvement in fat free lean index (FFLI) along with decreased back fat depth when they increased SID Trp:Lys ratio from 15 to 19.5% in 30% DDGS diets. A linear improvement in carcass yield and kilograms of carcass fat free lean were also demonstrated in the study by Guzik et al. (2005) that increased TID Trp from 0.06 to 0.14% in corn-feather meal diets. Mohn and Susenbeth (1994) also demonstrated a linear improvement in percentage lean when increasing total Trp from 0.10 to 0.18% in corn-pea-barley diets.

From the results of these trials, it is evident that increasing Trp in the diet provides an opportunity to improve carcass yield and lean percentage. There is some inconsistency in the response as some trials showed responses in both carcass yield and lean percentage whereas some found response in only one of the carcass traits. The variation between trials could be the result of different genetics that corresponds to the difference in lean deposition rate or the varying diet composition that can affect the carcass yield response. In creased Trp has been reported to accelerate gastric emptying time which results in smaller remaning meal content (Ponter et al., 1994). We believe this may explain the mechanism of Trp on improved carcass yield. In general, feeding higher in fiber diet has resulted in a decreased carcass yield that is due to increased gut content and increases in intestinal and organ weight (Whitney et al., 2006; Asmus, 2012). Feeding diets with high inclusion rate of DDGS has reported a similar effect as the fiber content in DDGS is approximately 3 times greater than in corn (Agyekum et al., 2012; Asmus, 2012; Graham, 2013). Therefore, the negative effect on carcass yield due to the high fiber content in DDGS may explain why increasing SID Trp:Lys ratio only benefited carcass yield in DDGS diet but not in corn-soybean meal diets in our studies.

In contrast to the growth data, carcass yield and leanness responses to increasing Trp did not plateau in most studies even at the highest Trp content used in the studies. The study by Guzik et al. (2005) also showed a greater Trp requirement for carcass fat free lean than the requirement for growth rate or feed efficiency when using the broken-line analysis. These observations may suggest a higher Trp requirement to maximize carcass value compared to the level required for maximum growth. Therefore, feeding above the Trp requirement for growth may offer a benefit from carcass value that has to be balanced against the higher feed cost when evaluating the economics of feeding higher dietary Trp.

Higher dietary crude protein has been reported to decrease growth performance at both adequate and sub-optimal Trp levels and could be due to the greater amount of LNAA (Henry et al., 1996). In Exp. 1, pigs fed the diet containing 21% SID Trp:Lys ratio from crystalline L-Trp had 4% better G:F than pigs fed the diet with increased soybean meal. Although, both diets were formulated to have similar nutrient content which met the requirements of pigs in that BW rage, the use of soybean meal to reach 21% SID Trp:Lys resulted in a greater excess amino acids and more crude protein content than in diets using crystalline L-Trp as the Trp source. Accordingly, the Trp:LNAA ratio in diet with soybean meal is lower than the diet with crystalline L-Trp (3.5 vs. 4.2, 3.3 vs. 3.9, and 4.0 vs. 4.9 in phase 1,2, and 3, respectively) due to a greater amount of LNAA. The interaction between LNAA and Trp that compete for absorption might explain the poorer feed efficiency observed in the diet with soybean meal in our study. Nevertheless, in the study by Salyer et al. (2013), no differences in growth performance was observed between pigs fed diet containing 18% SID Trp:Lys ratio from crystalline L-Trp and soybean meal. However, there was only a smaller difference in Trp:LNAA ratios between diets (3.4 vs. 3.7) in their trial. Another consideration is the excess of other essential and non-essential amino acids which increases energy cost from its catabolism and increased maintenance requirement, resulting in adverse feed efficiency which is a common effect when feeding excess protein (Noblet et al., 1987; Henry and Seve, 1993).

In summary, data from these experiments indicate there is potential opportunity to mitigate the negative effect of DDGS on carcass value by increasing dietary Trp concentrations.

Nevertheless, data on the effect of Trp on carcass traits is scarce and needs to be further investigated, including the economic evaluation of feeding an increased dietary Trp level.

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FIGURES AND TABLES

Table 3.1 Composition of diets, Exp.1 (Pretest and phase 1; as-fed basis)

Item	Pretest diet[1]	Trp source	
		L-Trp[2]	Soybean meal[3]
Ingredient, %			
Corn	52.20	60.04	51.47
Soybean meal, 46.5%	10.79	7.88	16.76
DDGS[4]	35.00	30.00	30.00
Limestone	1.15	1.15	1.15
Salt	0.35	0.35	0.35
Trace mineral premix	0.08	0.08	0.08
Vitamin premix	0.08	0.08	0.08
L-Lys HCl	0.36	0.41	0.12
L-Thr	---	0.03	---
L-Trp	---	---	---
TOTAL	100	100	100
Calculated analysis			
Standadized ileal digestible (SID) amino acids, %			
Lys	0.85	0.80	0.80
Ile:Lys	70	66	84
Leu:Lys	206	200	226
Met:Lys	36	34	40
Met & Cys:Lys	73	70	81
Thr:Lys	66	65	77
Trp:Lys	16.5	15.0	21.0
Val:Lys	87	83	101
Phe:Lys	93	88	108
Tyr:Lys	68	63	79
Trp:LNAA[5]	3.2	3.0	3.5
Trp:BCAA[6]	4.5	4.3	5.1
Total Lys, %	1.02	0.95	0.97
ME, kcal/kg	3,359	3,361	3,355
SID Lys:ME, g/Mcal	2.53	2.38	2.38
CP, %	19.3	17.3	20.4

Ca, %	0.50	0.49	0.52
P, %	0.47	0.44	0.47
Available P, %	0.23	0.20	0.21

[1] The pretest diet was fed for 3 wk before start of the experiment, from approximately 57- to 74-kg BW and phase 1 diets were fed from 74- to 95-kg BW.

[2] Crystalline L-Trp was added at 0.016, 0.032, and 0.048% of the diet to provide SID Trp:Lys ratios of 17, 19, and 21% of Lys.

[3] Soybean meal was used as the source of Trp to achieve a SID Trp:Lys ratio of 21% of Lys.

[4] Dried distillers grains with solubles.

[5]Amount of Trp in the diet as a ratio to large neutral amino acids (LNAA; Ile, Leu, Val, Phe, and Tyr) on a SID basis. The ratios were 3.0, 3.4, 3.8, and 4.2 % as increasing SID Trp:Lys from 15, 17, 19 , to 21%.

[6]Amount of Trp in the diet as a ratio to branched-chain amino acids (BCAA; Ile, Leu, Val) on SID basis. The ratios were 4.3, 4.9, 5.5, and 6.0 % as increasing SID Trp:Lys from 15, 17, 19 , to 21%.

Table 3.2 Composition of diets, Exp. 1 (Phase 2 and phase 3; as-fed basis)[1]

	Phase 2		Phase 3	
Trp source	Crystalline L-Trp[2]	Soybean meal[3]	Crystalline L-Trp[2]	Soybean meal
Ingredient, %				
Corn	62.99	55.45	69.46	59.82
Soybean meal, 46.5%	4.99	12.78	13.39	23.36
DDGS[4]	30.00	30.00	15.00	15.00
Limestone	1.15	1.15	1.10	1.10
Salt	0.35	0.35	0.35	0.35
Trace mineral premix	0.08	0.08	0.08	0.08
Vitamin premix	0.08	0.08	0.08	0.08
L-Lys HCl	0.37	0.12	0.41	0.09
DL-Met	---	---	0.015	---
L-Thr	---	---	0.09	0.09
L-Trp	---	---	---	---
Ractopamine HCl, 20 g/kg[5]	---	---	0.038	0.038
TOTAL	100	100	100	100
Calculated analysis				
Standadized ileal digestible (SID) amino acids,				
Lys	0.70	0.70	0.90	0.90
Ile:Lys	68	87	60	79
Leu:Lys	218	245	163	189
Met:Lys	37	43	30	34
Met & Cys:Lys	77	87	60	69
Thr:Lys	65	80	65	80
Trp:Lys	15.0	21.0	15.0	21.0
Val:Lys	88	106	73	91
Phe:Lys	93	113	77	97
Tyr:Lys	67	83	55	71
Trp:LNAA[6]	2.8	3.3	3.5	4.0
Trp:BCAA[7]	4.0	4.8	5.1	5.8
Total Lys, %	0.84	0.86	1.02	1.05
ME, kcal/kg	3,361	3,357	3,359	3,352
SID Lys:ME, g/Mcal	2.08	2.08	2.68	2.68
CP, %	16.2	18.9	16.7	20.2
Ca, %	0.48	0.51	0.49	0.52
P, %	0.42	0.46	0.39	0.44

Available P, %	0.20	0.21	0.13	0.14

[1] Phase 2 diets were fed from 95- to 113-kg BW and phase 3 diets were fed from 113 kg BW until market.

[2] Crystalline L-Trp was added at 0.014, 0.029, and 0.043% of the diet in phase 2 and at 0.018, 0.036, and 0.054% of the diet in phase 3 to provide SID Trp:Lys ratios of 17, 19, and 21% of Lys.

[3] Soybean meal was used as the source of Trp to achieve a SID Trp:Lys ratio of 21% of Lys.

[4] Dried distillers grains with solubles.

[5] Ractopamine HCl (Paylean; Elanco Animal Health, Greenfield, IN) at 7.5 ppm was added.

[6] Amount of Trp in the diet as a ratio to large neutral amino acids (LNAA; Ile, Leu, Val, Phe, and Tyr) on SID basis. The ratios were 2.8, 3.2, 3.6, and 3.9% in phase 2 and 3.5, 4.0, 4.4, and 4.9% in phase 3 as increasing SID Trp:Lys from 15, 17, 19 , to 21%.

[7] Amount of Trp in the diet as a ratio to branched-chain amino acids (BCAA; Ile, Leu, Val) on SID basis. The ratios were 4.0, 4.5, 5.1, and 5.6 in phase 2 and 5.1, 5.8, 6.4, and 7.1 % in phase 3 as increasing SID Trp:Lys from 15, 17, 19 , to 21%.

Table 3.3 Composition of diets, Exp. 2 (Phase 1; as-fed basis)[1]

	Phase 1					
DDGS,[2] %	0	30				0
SID Trp:Lys, %	17	15	17	19	21	21
Ingredient, %						
Corn	80.50	59.54	56.21	52.77	49.44	73.79
Soybean meal (47.5% CP)	16.70	8.43	11.58	14.83	17.98	23.09
DDGS	---	30.00	30.00	30.00	30.00	---
Choice white grease	0.53	---	0.32	0.64	0.95	1.21
Limestone	0.78	1.14	1.11	1.08	1.05	0.72
Monocalcium P (21% P)	0.68	---	---	---	---	0.65
Salt	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin–trace mineral premix	0.10	0.10	0.10	0.10	0.10	0.10
L-Lys HCl	0.26	0.38	0.29	0.18	0.09	0.06
L-Thr	0.08	0.02	0.01	0.01	---	---
DL-Met	0.01	---	---	---	---	---
TOTAL	100	100	100	100	100	100
Calculated analysis						
Standardized ileal digestible (SID) amino acids,						
Lys	0.82	0.82	0.82	0.82	0.82	0.82
Ile:Lys	62	67	74	80	86	74
Met:Lys[3]	29	35	36	38	40	31
Met & Cys:Lys	56	76	79	82	86	61
Thr:Lys	65	65	69	74	78	66
Trp:Lys	17	15	17	19	21	21
Val:Lys	72	85	91	97	103	84
Phe:Lys[3]	77	89	96	103	109	90
Tyr:Lys[3]	55	65	70	75	80	65
Trp:LNAA[4]	4.0	3.1	3.3	3.4	3.6	4.3
Trp:BCAA[5]	5.8	4.4	4.7	5.0	5.2	6.3
Total Lys, %	0.93	0.95	0.96	0.97	0.98	0.95
Modified ME,[6] kcal/kg	3,260	3,260	3,260	3,260	3,260	3,260
SID Lys:ME, g/Mcal	2.52	2.52	2.52	2.52	2.52	2.52
CP, %	14.9	17.4	18.6	19.7	20.9	17.2
Ca, %	0.60	0.60	0.60	0.60	0.60	0.60
P, %	0.57	0.52	0.53	0.55	0.56	0.59
Available P, %	0.30	0.30	0.31	0.31	0.31	0.30
SID Lys[3]	0.83	0.80	0.81	0.81	0.81	0.83

SID Trp:Lys,[3] %	17.0	15.6	17.6	19.8	21.7	21.0
ME,[7] kcal/kg	3,370	3,361	3,374	3,388	3,401	3,399

[1] Phase 1 experimental diets were fed from d 0 to 21 (71.4- to 95-kg BW).
[2] Dried distillers grains with solubles.
[3] SID Met, SID Phe, SID Tyr, SID Lys, SID Trp:Lys (%), and ME (kcal/kg) were calculated using NRC (1998) values.
[4] Amount of Trp in the diet as a ratio to large neutral amino acids (LNAA; Ile, Leu, Val, Phe, and Tyr) on SID basis.
[5] Amount of Trp in the diet as a ratio to branched-chain amino acids (BCAA; Ile, Leu, Val) on SID basis.
[6] Modified ME was calculated by Hanor company.
[7] All energy levels used to calculate ME were based on NRC (1998) values except DDGS, where the energy value of corn was used.

Table 3.4 Composition of diets, Exp. 2 (Phase 2; as-fed basis)[1]

	Phase 2					
DDGS,[2] %	0	30				0
SID Trp:Lys,%	17	15	17	19	21	21
Ingredient, %						
Corn	83.85	62.41	59.45	56.40	53.43	77.96
Soybean meal (47.5% CP)	13.43	5.53	8.31	11.17	13.95	19.04
DDGS	---	30.00	30.00	30.00	30.00	---
Choice white grease	0.60	0.11	0.41	0.71	1.00	1.19
Limestone	0.83	1.12	1.09	1.06	1.04	0.79
Monocalcium P (21% P)	0.51	---	---	---	---	0.48
Salt	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin–trace mineral premix	0.10	0.10	0.10	0.10	0.10	0.10
L-Lys	0.23	0.34	0.26	0.17	0.09	0.06
L-Thr	0.65	---	---	---	---	---
TOTAL	100	100	100	100	100	100
Calculated analysis						
Standardized ileal digestible (SID) amino acids,						
Lys	0.72	0.72	0.72	0.72	0.72	0.72
Ile:Lys	63	70	77	83	89	76
Met:Lys[3]	29	38	40	41	43	33
Met & Cys:Lys	58	83	86	89	93	65
Thr:Lys	66	66	71	77	82	67
Trp:Lys	17	15	17	19	21	21
Val:Lys	75	91	97	103	109	87
Phe:Lys[3]	80	96	102	108	114	93
Tyr:Lys[3]	56	68	74	79	84	66
Trp:LNAA[4]	3.8	2.9	3.1	3.2	3.4	4.1
Trp:BCAA[5]	5.5	4.1	4.4	4.7	4.9	6.0
Total Lys, %	0.81	0.83	0.85	0.86	0.87	0.83
Modified ME,[6] kcal/kg	3,282	3,282	3,282	3,282	3,282	3,282
SID Lys:ME, g/Mcal	2.20	2.20	2.20	2.20	2.20	2.20
CP, %	13.6	16.3	17.3	18.3	19.3	15.6
Ca, %	0.58	0.58	0.58	0.58	0.58	0.58
P, %	0.52	0.51	0.52	0.53	0.54	0.53
Available P, %	0.26	0.30	0.30	0.31	0.31	0.26
SID Lys[3]	0.72	0.69	0.70	0.70	0.71	0.73

SID Trp:Lys,[3] %	16.9	15.7	17.7	19.8	21.8	21.0
ME,[7] kcal/kg	3,379	3,368	3,381	3,392	3,405	3,403

[1] Phase 2 experimental diets were fed from d 21 to 42 (95- to 113-kg BW).
[2] Dried distillers grains with solubles.
[3] SID Met, SID Phe, SID Tyr, SID Lys, SID Trp:Lys (%), and ME (kcal/kg) were calculated using NRC (1998) values.
[4] Amount of Trp in the diet as a ratio to large neutral amino acids (LNAA; Ile, Leu, Val, Phe, and Tyr) on SID basis.
[5] Amount of Trp in the diet as a ratio to branched-chain amino acids (BCAA; Ile, Leu, Val) on SID basis.
[6] Modified ME was calculated by Hanor company.
[7] All energy levels used to calculate ME were based on NRC (1998) values except DDGS, where the energy value of corn was used.

Table 3.5 Composition of diets, Exp. 2 (Phase 3; as-fed basis)[1]

	Phase 3					
DDGS,[2] %	0	30				0
SID Trp:Lys,%	17	15	17	19	21	21
Ingredient, %						
Corn	86.02	72.58	69.92	67.18	64.53	80.67
Soybean meal (47.5% CP)	11.42	5.44	7.97	10.59	13.13	16.54
DDGS	---	20.00	20.00	20.00	20.00	---
Choice white grease	0.45	---	0.25	0.50	0.75	0.95
Limestone	0.84	1.09	1.08	1.06	1.04	0.81
Monocalcium P (21% P)	0.52	0.07	0.05	0.02	---	0.49
Salt	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin–trace mineral premix	0.10	0.10	0.10	0.10	0.10	0.10
L-Lys HCl	0.22	0.31	0.23	0.15	0.08	0.06
L-Thr	0.05	0.02	---	---	---	---
TOTAL	100	100	100	100	100	100
Calculated analysis						
Standardized ileal digestible (SID) amino acids,						
Lys	0.66	0.66	0.66	0.66	0.66	0.66
Ile:Lys	64	68	74	80	86	77
Met:Lys[3]	31	37	38	40	42	34
Met & Cys:Lys	61	78	81	85	88	68
Thr:Lys	66	66	70	75	79	69
Trp:Lys	17	15	17	19	21	21
Val:Lys	77	87	93	99	105	89
Phe:Lys[3]	82	92	99	105	111	95
Tyr:Lys[3]	57	65	70	75	80	68
Trp:LNAA[4]	3.7	2.9	3.1	3.3	3.5	4.0
Trp:BCAA[5]	5.3	4.2	4.5	4.8	5.0	5.8
Total Lys, %	0.74	0.76	0.76	0.78	0.79	0.76
Modified ME,[6] kcal/kg	3,282	3,282	3,282	3,282	3,282	3,282
SID Lys:ME, g/Mcal	2.01	2.01	2.01	2.01	2.01	2.01
CP, %	12.8	14.3	15.2	16.2	17.1	14.6
Ca, %	0.58	0.58	0.58	0.58	0.58	0.58
P, %	0.51	0.48	0.48	0.49	0.50	0.53
Available P, %	0.26	0.26	0.26	0.26	0.26	0.26
SID Lys[3]	0.66	0.64	0.64	0.65	0.65	0.67

SID Trp:Lys,[3] %	16.9	15.4	17.5	19.6	21.5	20.9
ME,[7] kcal/kg	3,372	3,361	3,372	3,383	3,394	3,392

[1] Phase 3 experimental diets were fed from d 42 to market (113- to 125-kg BW).
[2] Dried distillers grains with solubles.
[3] SID Met, SID Phe, SID Tyr, SID Lys, SID Trp:Lys (%), and ME (kcal/kg) were calculated using NRC (1998) values.
[4] Amount of Trp in the diet as a ratio to large neutral amino acids (LNAA; Ile, Leu, Val, Phe, and Tyr) on SID basis.
[5] Amount of Trp in the diet as a ratio to branched-chain amino acids (BCAA; Ile, Leu, Val) on SID basis.
[6] Modified ME was calculated by Hanor company.
[7]All energy levels used to calculate ME were based on NRC (1998) values except DDGS, where the energy value of corn was used.

Table 3.6 Composition of diets, Exp. 3 (Phase 1; as-fed basis)[1]

			SID Trp:Lys, %					
	Common		16.5			20		
Item	diet[1]	DDGS[2], %	0	20	40	0	20	40
Ingredient, %								
Corn	53.60		82.70	66.40	50.00	77.90	61.60	45.20
Soybean meal, 46.5% CP	14.40		15.10	11.50	7.80	20.30	16.60	12.90
DDGS	30.00		---	20.00	40.00	---	20.00	40.00
Monocalcium P, 21% P	---		0.35	---	---	0.33	---	---
Limestone	1.15		0.95	1.15	1.18	0.93	1.10	1.13
Salt	0.35		0.35	0.35	0.35	0.35	0.35	0.35
Vitamin–trace mineral premix[3]	---		0.09	0.09	0.09	0.09	0.09	0.09
L-Thr	---		0.08	0.02	---	---	---	---
Biolys[4]	0.50		0.42	0.49	0.56	0.16	0.23	0.30
Phytase[5]	0.01		0.01	0.01	0.01	0.01	0.01	0.01
TOTAL	100		100	100	100	100	100	100
Calculated analysis								
SID amino acids, %								
Lys	0.90		0.79	0.79	0.79	0.79	0.79	0.79
Ile:Lys	71		62	68	73	73	79	84
Leu:Lys	195		158	191	224	174	207	240
Met:Lys	34		28	33	39	31	36	42
Met & Cys:Lys	70		57	68	79	63	74	85
Thr:Lys	65		65	65	69	65	71	78
Trp:Lys	17.3		16.5	16.5	16.5	20.0	20.0	20.0
Val:Lys	86		74	83	93	85	94	103
Phe:Lys	91		77	88	98	89	100	110
Tyr:Lys	67		55	63	72	64	72	81
Trp:LNAA[6]	3.4		3.9	3.4	2.9	4.1	3.6	3.2
Trp:BCAA[7]	4.9		5.6	4.8	4.2	6.0	5.3	4.7
Total Lys, %	1.06		0.88	0.92	0.96	0.90	0.93	0.97
ME, kcal/kg	3,363		3,355	3,361	3,363	3,352	3,359	3,361
SID Lys:ME, g/Mcal	2.67		2.35	2.35	2.35	2.35	2.35	2.35
CP, %	19.8		14.4	16.8	19.2	16.2	18.6	21.0
Ca, %	0.51		0.50	0.50	0.50	0.50	0.50	0.50
P, %	0.46		0.41	0.41	0.48	0.43	0.43	0.50
Available P, %	0.31		0.23	0.26	0.35	0.23	0.26	0.36

[1] Common diet was fed from 45- to 68-kg of pig BW; Phase 1 diet was an experimental diet fed from 68 to 89 kg.

[2] Dried distillers grains with solubles from Valero (Aurora, SD).

[3] Provided per kg of premix: 4,509,409 IU vitamin A; 701,464 IU vitamin D3; 24,050 IU vitamin E; 1,402 mg vitamin K; 12,025 pantothenic acid; 18,037 mg niacin; 3,006 mg vitamin B2 and 15,031 mg vitamin B12, 40,084 mg Mn from manganese oxide, 90,188 mg Fe from iron sulfate, 100,209 Zn from zinc oxide, 10,021 mg Cu from copper sulfate, 501 mg I from Ethylenediamin dihydroiodide, and 300 mg Se from sodium selenite.

[4] Biolys® contains 50.7% L-Lys in the form of L-Lys sulfate (Evonik Degussa GmbH, Hanau, Germany).

[5] OptiPhos 2000 (Enzyvia LLC, Sheridan, IN) provided 500 FTU per kg of diet.

[6] Amount of Trp in the diet as a ratio to large neutral amino acids (LNAA; Ile, Leu, Val, Phe, and Tyr) on SID basis.

Table 3.7 Composition of diets, Exp. 3 (Phase 2; as-fed basis)[1]

	SID Trp:Lys, %					
	16.5			20		
Item DDGS[2],%	0	20	40	0	20	40
Ingredient, %						
Corn	85.5	69.2	52.8	81.2	65.0	48.4
Soybean meal, 46.5% CP	12.3	8.7	5.1	16.9	13.2	9.7
DDGS	---	20.00	40.00	---	20.00	40.00
Monocalcium P, 21% P	0.35	---	---	0.35	---	---
Limestone	0.98	1.18	1.20	0.93	1.13	1.15
Salt	0.35	0.35	0.35	0.35	0.35	0.35
Vitamin–trace mineral premix [3]	0.09	0.09	0.09	0.09	0.09	0.09
L-Thr	0.05	---	---	---	---	---
Biolys[4]	0.38	0.45	0.52	0.15	0.22	0.29
Phytase[5]	0.01	0.01	0.01	0.01	0.01	0.01
TOTAL	100	100	100	100	100	100
Calculated analysis						
SID amino acids, %						
Lys	0.70	0.70	0.70	0.70	0.70	0.70
Ile:Lys	64	70	76	75	81	87
Leu:Lys	169	207	244	184	222	259
Met:Lys	29	36	42	33	39	45
Met & Cys:Lys	61	73	86	67	79	92
Thr:Lys	65	65	73	67	74	82
Trp:Lys	16.5	16.5	16.5	20.0	20.0	20.0
Val:Lys	77	88	98	88	98	109
Phe:Lys	80	92	104	92	104	116
Tyr:Lys	56	66	75	65	75	85
Trp:LNAA[6]	3.7	3.2	2.8	4.0	3.4	3.0
Trp:BCAA[7]	5.3	4.5	3.9	5.8	5.0	4.4
Total Lys, %	0.79	0.82	0.86	0.80	0.84	0.87
ME, kcal/kg	3,355	3,361	3,363	3,352	3,359	3,361
SID Lys:ME, g/Mcal	2.08	2.08	2.08	2.09	2.08	2.08
CP, %	13.3	15.7	18.1	14.9	17.3	19.7
Ca, %	0.50	0.50	0.50	0.50	0.50	0.50
P, %	0.40	0.40	0.47	0.42	0.42	0.49

Available P, %	0.23	0.25	0.35	0.24	0.26	0.36

[1] Phase 2 diet was fed from 89- to 109-kg BW.

[2] Dried distillers grains with solubles from Valero (Aurora, SD).

[3] Provided per kg of premix: 4,509,409 IU vitamin A; 701,464 IU vitamin D3; 24,050 IU vitamin E; 1,402 mg vitamin K; 12,025 pantothenic acid; 18,037 mg niacin; 3,006 mg vitamin B2 and 15,031 mg vitamin B12, 40,084 mg Mn from manganese oxide, 90,188 mg Fe from iron sulfate, 100,209 Zn from zinc oxide, 10,021 mg Cu from copper sulfate, 501 mg I from Ethylenediamin dihydroiodide, and 300 mg Se from sodium selenite.

[4] Biolys® contains 50.7% L-Lys in the form of L-Lys sulfate (Evonik Degussa GmbH, Hanau, Germany).

[5] OptiPhos 2000 (Enzyvia LLC, Sheridan, IN) provided 500 FTU per kg of diet.

[6] Amount of Trp in the diet as a ratio to large neutral amino acids (LNAA; Ile, Leu, Val, Phe, and Tyr) on SID basis.

[7] Amount of Trp in the diet as a ratio to branched-chain amino acids (BCAA; Ile, Leu, Val) on SID basis.

Table 3.8 Composition of diets, Exp. 3 (Phase 3; as-fed basis)[1]

		SID Trp:Lys ratio, %					
		16.5			20		
Item	DDGS[2],%	0	20	40	0	20	40
Ingredient, %							
Corn		85.50	69.20	52.80	81.20	65.00	48.40
Soybean meal, 46.5% CP		12.30	8.70	5.10	16.90	13.20	9.70
DDGS		---	20.00	40.00	---	20.00	40.00
Monocalcium P, 21% P		0.35	---	---	0.35	---	---
Limestone		0.98	1.18	1.20	0.93	1.13	1.15
Salt		0.35	0.35	0.35	0.35	0.35	0.35
Vitamin–trace mineral premix[3]		0.09	0.09	0.09	0.09	0.09	0.09
DL-Met		0.05	---	---	---	---	---
L-Thr		0.05	---	---	---	---	---
Biolys[4]		0.38	0.45	0.52	0.15	0.22	0.29
Phytase[5]		0.01	0.01	0.01	0.01	0.01	0.01
Ractopamine HCl, 20 g/kg[6]		0.05	0.05	0.05	0.05	0.05	0.05
TOTAL		100	100	100	100	100	100
Calculated analysis							
SID amino acids, %							
Lys		0.92	0.92	0.92	0.92	0.92	0.92
Ile:Lys		61	63	66	72	74	76
Leu:Lys		146	160	174	161	176	190
Met:Lys		31	28	31	29	31	34
Met & Cys:Lys		58	58	63	59	64	69
Thr:Lys		65	65	65	65	66	69
Trp:Lys		16.5	16.6	16.5	20.0	20.0	20.0
Val:Lys		71	75	79	82	86	90
Phe:Lys		74	79	83	86	90	95
Tyr:Lys		53	57	60	62	66	70
Trp:LNAA[7]		4.1	3.8	3.6	4.3	4.1	3.8
Trp:BCAA[8]		6.0	5.5	5.2	6.4	6.0	5.6
Total Lys, %		1.02	1.04	1.06	1.04	1.06	1.08
ME, kcal/kg		3,355	3,359	3,359	3,350	3,357	3,357
SID Lys:ME, g/Mcal		2.74	2.74	2.74	2.74	2.74	2.74
CP, %		16.0	17.2	18.4	18.0	19.2	20.4
Ca, %		0.50	0.50	0.50	0.50	0.50	0.50

P, %	0.42	0.39	0.42	0.44	0.41	0.45
Available P, %	0.23	0.21	0.26	0.23	0.22	0.27

[1] Phase 3 diet was fed from 109 kg until market (137 kg BW).
[2] Dried distillers grains with solubles from Valero (Aurora, SD).
[3] Provided per kg of premix: 4,509,409 IU vitamin A; 701,464 IU vitamin D3; 24,050 IU vitamin E; 1,402 mg vitamin K; 12,025 pantothenic acid; 18,037 mg niacin; 3,006 mg vitamin B2 and 15,031 mg vitamin B12, 40,084 mg Mn from manganese oxide, 90,188 mg Fe from iron sulfate, 100,209 Zn from zinc oxide, 10,021 mg Cu from copper sulfate, 501 mg I from Ethylenediamin dihydroiodide, and 300 mg Se from sodium selenite.
[4] Biolys® contains 50.7% L-Lys in the form of L-Lys sulfate (Evonik Degussa GmbH, Hanau, Germany).
[5] OptiPhos 2000 (Enzyvia LLC, Sheridan, IN) provided 500 FTU per kg of diet.
[6] Ractopamine HCl (Paylean; Elanco Animal Health, Greenfield, IN) at 10 ppm was added.
[7] Amount of Trp in the diet as a ratio to large neutral amino acids (LNAA; Ile, Leu, Val, Phe, and Tyr) on SID basis.
[8] Amount of Trp in the diet as a ratio to branched-chain amino acids (BCAA Ile, Leu, Val) on SID basis.

Table 3.9 Total AA analysis of Exp. 1 diets (Phase 1; as-fed basis)[1]

Diet	Phase 1				
SID Trp:Lys, %	15[2]	17	19	21	Soybean meal 21[3]
Total AA, %					
Lys	0.86 (0.95)[2]	0.85 (0.95)	0.90 (0.95)	0.89 (0.95)	1.00 (0.97)
Trp	0.15 (0.15)	0.16 (0.16)	0.18 (0.18)	0.18 (0.19)	0.20 (0.20)
Free Trp	0.003 (---)	0.02 (0.02)	0.03 (0.03)	0.04 (0.05)	0.006 (---)
Thr	0.60 (0.66)	0.61 (0.66)	0.62 (0.66)	0.61 (0.66)	0.75 (0.78)
Met	0.30 (0.32)	0.30 (0.32)	0.30 (0.32)	0.30 (0.32)	0.35 (0.36)
Cys	0.29 (0.34)	0.30 (0.34)	0.30 (0.34)	0.30 (0.34)	0.33 (0.39)
Met + Cys	0.59 (0.66)	0.60 (0.66)	0.60 (0.66)	0.60 (0.66)	0.68 (0.76)
Ile	0.58 (0.64)	0.61(0.64)	0.57 (0.64)	0.56 (0.64)	0.77 (0.81)
Leu	1.68 (1.83)	1.72 (1.83)	1.64 (1.83)	1.63 (1.83)	1.91 (2.07)
Val	0.76 (0.82)	0.78 (0.82)	0.77 (0.82)	0.76 (0.82)	0.92 (0.99)

[1] Diet samples of each phase were analyzed for total amino acid content by Ajinomoto Heartland LLC (Chicago, IL) and Evonik Degussa Corporation (Kennesaw, GA). The reported values were the average AA contents of the two labs.
[2] Values in parentheses indicate formulated values.

Table 3.10 Total AA analysis of Exp. 1 diets (Phase 2; as-fed basis)[1]

Diet	Phase 2				
SID Trp:Lys, %	15[2]	17	19	21	Soybean meal 21[3]
Total AA, %					
Lys	0.88 (0.84)[2]	0.86 (0.84)	0.77 (0.84)	0.81 (0.84)	0.90 (0.86)
Trp	0.14 (0.13)	0.15 (0.15)	0.15 (0.16)	0.17 (0.17)	0.18 (0.17)
Free Trp	0.003 (---)	0.01 (0.01)	0.02 (0.03)	0.04 (0.04)	0.005 (---)
Thr	0.58 (0.59)	0.59 (0.59)	0.59 (0.59)	0.61 (0.59)	0.69 (0.72)
Met	0.29 (0.31)	0.30 (0.31)	0.30 (0.31)	0.32 (0.31)	0.33 (0.34)
Cys	0.30 (0.33)	0.29 (0.33)	0.30 (0.33)	0.31 (0.33)	0.33 (0.37)
Met + Cys	0.59 (0.63)	0.59 (0.63)	0.60 (0.63)	0.63 (0.63)	0.66 (0.72)
Ile	0.56 (0.59)	0.57 (0.59)	0.54 (0.59)	0.54 (0.59)	0.71 (0.73)
Leu	1.65 (1.76)	1.67 (1.76)	1.62 (1.76)	1.65 (1.76)	1.83 (1.97)
Val	0.74 (0.76)	0.74 (0.76)	0.74 (0.76)	0.76 (0.76)	0.87 (0.91)

[1] Diet samples of each phase were analyzed for total amino acid content by Ajinomoto Heartland LLC (Chicago, IL) and Evonik Degussa Corporation (Kennesaw, GA). The reported values were the average AA contents of the two labs.

[2] Values in parentheses indicate formulated values.

Table 3.11 Total AA analysis of Exp. 1 diets (Phase 3; as-fed basis)[1]

Diet	Phase 3				
SID Trp:Lys, %	15[2]	17	19	21	Soybean meal 21[3]
Total AA, %					
Lys	1.00 (1.02) [2]	1.01 (1.02)	1.03 (1.02)	1.13 (1.02)	1.16 (1.05)
Trp	0.16 (0.15)	0.18 (0.17)	0.20 (0.19)	0.21 (0.21)	0.22 (0.21)
Free Trp	0.005 (---)	0.02 (0.02)	0.03 (0.04)	0.05 (0.05)	0.008 (---)
Thr	0.66 (0.70)	0.68 (0.70)	0.71 (0.70)	0.72 (0.70)	0.81 (0.85)
Met	0.28 (0.31)	0.28 (0.31)	0.30 (0.31)	0.30 (0.31)	0.33 (0.34)
Cys	0.28 (0.32)	0.28 (0.32)	0.28 (0.32)	0.29 (0.32)	0.32 (0.37)
Met + Cys	0.56 (0.62)	0.56 (0.62)	0.58 (0.62)	0.59 (0.62)	0.65 (0.71)
Ile	0.60 (0.64)	0.61 (0.64)	0.60 (0.64)	0.67 (0.64)	0.82 (0.82)
Leu	1.49 (1.65)	1.50 (1.65)	1.51 (1.65)	1.53 (1.65)	1.82 (1.92)
Val	0.74 (0.78)	0.74 (0.78)	0.76 (0.78)	0.79 (0.78)	0.94 (0.97)

[1] Diet samples of each phase were analyzed for total amino acid content by Ajinomoto Heartland LLC (Chicago, IL) and Evonik Degussa Corporation (Kennesaw, GA). The reported values were the average AA contents of the two labs.
[2] Values in parentheses indicate formulated values.

Table 3.12 Total AA analysis of Exp.2 diets (as-fed basis)[1]

Diet	Phase 1				Phase 2				Phase 3			
DDGS, %	0		30		0		30		0		30	
SID Trp:Lys, %	17	21	15	21	17	21	15	21	17	21	15	21
Total AA, %												
Lys	0.80 (0.93)[2]	0.87 (0.95)	0.93 (0.95)	0.96 (0.98)	0.82 (0.81)	0.86 (0.83)	0.86 (0.83)	0.91 (0.87)	0.73 (0.74)	0.73 (0.76)	0.78 (0.76)	0.79 (0.79)
Trp	0.15 (0.16)	0.20 (0.20)	0.18 (0.15)	0.23 (0.21)	0.16 (0.14)	0.19 (0.17)	0.17 (0.14)	0.21 (0.19)	0.15 (0.13)	0.17 (0.16)	0.14 (0.12)	0.18 (0.17)
Thr	0.54 (0.63)	0.61 (0.65)	0.62 (0.66)	0.73 (0.80)	0.55 (0.56)	0.59 (0.59)	0.59 (0.60)	0.71 (0.74)	0.52 (0.51)	0.52 (0.55)	0.51 (0.54)	0.63 (0.65)
Met	0.23 (0.26)	0.26 (0.28)	0.31 (0.32)	0.34 (0.37)	0.23 (0.23)	0.25 (0.26)	0.30 (0.31)	0.34 (0.35)	0.22 (0.22)	0.23 (0.25)	0.26 (0.27)	0.30 (0.31)
Cys	0.24 (0.28)	0.28 (0.31)	0.31 (0.35)	0.35 (0.40)	0.24 (0.26)	0.27 (0.29)	0.30 (0.33)	0.35 (0.38)	0.24 (0.25)	0.25 (0.28)	0.26 (0.29)	0.31 (0.34)
Met + Cys	0.46 (0.54)	0.53 (0.60)	0.61 (0.67)	0.68 (0.77)	0.48 (0.50)	0.53 (0.55)	0.59 (0.64)	0.68 (0.73)	0.46 (0.47)	0.49 (0.53)	0.51 (0.56)	0.61 (0.65)
Ile	0.50 (0.59)	0.65 (0.72)	0.60 (0.66)	0.77 (0.84)	0.53 (0.53)	0.63 (0.64)	0.58 (0.60)	0.75 (0.76)	0.49 (0.49)	0.55 (0.59)	0.49 (0.53)	0.65 (0.67)
Leu	1.16 (1.42)	1.37 (1.59)	1.55 (1.86)	1.78 (2.11)	1.18 (1.33)	1.34 (1.48)	1.52 (1.78)	1.75 (2.00)	1.16 (1.28)	1.22 (1.42)	1.28 (1.56)	1.55 (1.76)

Val	0.60 (0.70)	0.74 (0.82)	0.77 (0.83)	0.93 (1.01)	0.63 (0.64)	0.72 (0.75)	0.75 (0.78)	0.90 (0.94)	0.59 (0.60)	0.65 (0.70)	0.63 (0.68)	0.79 (0.83)
Phe	0.63 (0.64)	0.78 (0.75)	0.76 (0.71)	0.94 (0.88)	0.65 (0.58)	0.76 (0.68)	0.74 (0.66)	0.91 (0.81)	0.61 (0.54)	0.68 (0.63)	0.63 (0.59)	0.79 (0.72)
Tyr	0.29 (0.45)	0.38 (0.54)	0.42 (0.52)	0.50 (0.65)	0.30 (0.41)	0.39 (0.49)	0.41 (0.47)	0.50 (0.59)	0.31 (0.38)	0.34 (0.45)	0.31 (0.41)	0.43 (0.52)

[1] Diet samples of each phase were analyzed for total amino acid content by Ajinomoto Heartland LLC (Chicago, IL) and Evonik Degussa Corporation (Kennesaw, GA). The reported values were the average AA contents of the two labs.

[2] Values in parentheses indicate formulated values.

Table 3.13 Determining the effects of standardized ileal digestible (SID) Trp:Lys ratio in diets containing 30% dried distillers grains with solubles (DDGS) on growth performance of finishing pigs (Exp. 1) [1]

	SID Trp:Lys ratio, %						Probability, $P <$		
							Trp		21%
Item	15[2]	17	19	21	Soybean meal 21[3]	SEM	Linear	Quadratic	(crystalline L-Trp vs. Soybean meal)
Replications	6	6	6	6	6				
Initial BW, kg	74.1	74.2	74.1	74.1	74.2	0.98	0.99	0.92	0.94
Final BW, kg	131.8	130.4	131.2	129.7	128.1	2.07	0.55	1.00	0.59
<u>d 0 to 61</u>									
ADG , g	995	983	990	963	933	23.1	0.40	0.75	0.37
ADFI, g	3,312	3,320	3,276	3,203	3,226	70.3	0.25	0.58	0.82
G:F	0.300	0.296	0.302	0.301	0.289	0.003	0.61	0.64	0.01
SID Trp g/kg gain[4]	4.0	4.6	5.0	5.5	5.8	0.05	0.01	0.67	0.01

[1] A total of 845 pigs (PIC 380 × Monsanto; initially 74 kg BW) were used in a 61-d growing-finishing trial with 25 to 30 pigs per pen and 6 pens per treatment.
[2] Crystalline L-Trp was added to the 15% SID Trp:Lys diet to provide SID Trp:Lys ratios 17, 19, and 21% of Lys.
[3] Soybean meal was used as the source of Trp to provide a SID Trp:Lys ration of 21%.
[4] Calculated % SID Trp in diet was used in the calculation of gram of SID Trp intake per kg of BW gain.

Table 3.14 Effects of standardized ileal digestible (SID) Trp:Lys ratios in diets containing 30% dried distillers grains with solubles (DDGS) on growth performance of 71.4- to 125-kg pigs (Exp. 2)[1]

								Probability, $P <$			
DDGS, %	0		30					DDGS[3]	17 vs.21% Trp:Lys in corn-soy	Trp	
SID Trp:Lys,%	17	21	15	17	19	21	SEM			Linear	Quadratic
Replications[2]	17	17	17	16	16	17					
Initial BW, kg	71.3	71.4	71.4	71.4	71.4	71.5	1.4	0.96	0.97	0.98	0.96
Final BW, kg	127.1	126.3	124.7	123.7	125.6	124.2	1.2	0.02	0.65	0.92	0.85
d 0 to 52											
ADG, g	894	917	863	854	894	858	9.1	0.01	0.12	0.52	0.27
ADFI, g	2,915	2,906	2,874	2,833	2,919	2,824	36.3	0.04	0.88	0.72	0.50
G:F	0.307	0.315	0.299	0.300	0.306	0.303	0.018	0.01	0.09	0.26	0.63
SID Trp g/kg gain[4]	4.0	4.8	3.6	4.1	4.6	5.1	---	---	---	---	---
Carcass wt, kg	93.5	93.4	91.7	91.2	92.8	92.2	0.41	0.01	0.89	0.07	0.98
Carcass yield, %	73.8	73.9	73.2	73.4	73.8	74.4	0.31	0.99	0.80	0.01	0.42
Backfat depth,[5] mm	21.4	20.8	21.3	21.1	20.9	21.2	0.20	1.00	0.04	0.69	0.24
Loin depth, mm	59.8	60.4	59.6	59.1	59.8	59.2	0.30	0.01	0.15	0.79	0.73
Lean, %	52.1	52.4	52.1	52.1	52.2	52.0	0.11	0.04	0.04	0.70	0.44

[1] A total of 2,298 pigs (gilts and barrows, PIC TR4 × 1050; initially 71.4 kg) were used in a 52-d late finishing trial with 23 pigs per pen and 16 to 17 pens per treatment.

[2] Replications are numbers of pens for each treatment.

[3] Main effect of level of DDGS was analyzed by comparing between 17 and 21% SID Trp:Lys ratio in corn-soybean meal diet with 17 and 20% SID Trp:Lys ratio in 30% DDGS diet.

[4] Calculated % SID Trp in diet was used in the calculation of gram of SID Trp intake per kg of BW gain.

[5] Analysis of backfat depth, loin depth, and percentage of lean were adjusted to a common carcass weight using hot carcass weight as a covariate.

Table 3.15 Effects of Trp:Lys ratio in diets containing increasing dried distillers grains with solubles (DDGS) on growth performance of finishing pigs (Exp. 3)[1]

	SID Trp:Lys ratio, %							Probability, $P <$				
	16.5			20					DDGS		Trp × DDGS	
DDGS, %	0	20	40	0	20	40	SEM	Trp level	Linear	Quadratic	Linear	Quadratic
Replications[2]	8	7	8	8	7	8						
Initial BW, kg	67.9	67.6	67.8	67.8	67.9	67.6	1.38	1.00	0.93	0.98	1.00	0.86
Final BW, kg	136.1	136.8	135.7	137.4	138.1	136.6	1.47	0.35	0.70	0.45	0.86	0.93
d 0 to 71												
ADG , g	989	1,004	989	1,011	1,011	990	9.5	0.23	0.27	0.14	0.30	0.80
ADFI, g	2,933	3,015	3,060	3,029	3,066	3,008	40.3	0.36	0.20	0.37	0.07	0.70
G:F	0.337	0.333	0.323	0.334	0.330	0.329	0.004	0.91	0.02	0.86	0.25	0.49
SID Trp g/kg gain[3]	3.9	4.0	4.1	4.8	4.9	4.9	0.05	0.01	0.03	0.90	0.33	0.67
Carcass wt, kg	104.1	104.3	102.2	104.9	104.7	104.2	1.23	0.32	0.29	0.55	0.63	0.66
Carcass yield, %	77.6	76.5	76.8	77.2	78.2	78.0	0.41	0.02	0.96	0.85	0.07	0.10
Backfat depth,[4] mm.	17.7	18.4	17.8	18.7	18.8	17.4	0.44	0.54	0.19	0.13	0.09	0.84
Loin depth, mm.	72.7	73.3	70.1	74.2	71.8	72.6	0.77	0.24	0.01	0.83	0.51	0.02
Lean, %	56.8	55.8	55.8	56.4	56.0	56.7	0.36	0.40	0.37	0.13	0.08	0.99

[1] A total of 1,235 pigs (PIC 1050 × 337, initially 68 kg) were used in a 71-d growing-finishing trial with 26 to 28 pigs per pen and 7 to 8 pens per treatment.

[2] Replications are numbers of pens for each treatment.

[3] Calculated % SID Trp in diet was used in the calculation of gram of SID Trp intake per kg of BW gain.

[4] Analysis of backfat depth, loin depth, and percentage lean were adjusted to a common carcass weight.

Chapter 4 - The Effects of Standardized Ileal Digestible Tryptophan:Lysine Ratio and Tryptophan Source in Diets Containing Dried Distillers Grains with Solubles on Growth Performance and Carcass Characteristics of Finishing Pigs

ABSTRACT

A total of 2,290 pigs (PIC 1050 × 337; initially 71 kg) were used to determine the effect of Trp level and source in diets containing 30% dried distillers grains with solubles (DDGS) on finishing pig performance. Pens of pigs were allotted to 1 of 7 dietary treatments in a completely randomized design with 26 to 28 pigs per pen and 10 to 13 pens per treatment. Treatments were arranged as a 2 × 3 factorial with the main effects of Trp source (crystalline L-Trp or soybean meal) and standardized ileal digestible (SID) Trp:Lys ratio (18, 20, or 22%). The 7th treatment was a negative control diet formulated to 16% SID Trp:Lys. Overall, ADG improved (quadratic, $P < 0.01$) as the SID Trp:Lys ratio increased to 20%. A Trp source × SID Trp:Lys ratio interaction ($P = 0.03$) was observed for G:F. Increasing SID Trp:Lys to 20% improved (quadratic, $P < 0.01$) G:F when soybean meal was the source of Trp, but the optimum ratio was 18% with crystalline L-Trp. Increasing SID Trp:Lys increased (linear, $P = 0.01$) carcass yield when using crystalline L-Trp; however, increasing SID Trp:Lys with soybean meal demonstrated (quadratic, $P = 0.03$) the greatest carcass yield at 18% SID Trp:Lys with smaller response at 20 and 22% (interaction, $P = 0.01$). Loin depth was greatest for the control diet and lowest at 18% SID Trp:Lys (quadratic, $P = 0.02$). For the main effect of Trp source, no differences were observed in ADFI between sources; however, a trend ($P = 0.07$) was observed for greater ADG when using soybean meal as the Trp source. Backfat depth was greater ($P = 0.04$) and percentage lean ($P =$

0.02) was lower in pigs fed with crystalline L-Trp than those with soybean meal as the Trp source. This study indicates an optimum SID Trp:Lys ratio of 20% for 71- to 127-kg pigs fed high level of DDGS. Using soybean meal or crystalline L-Trp provided a similar response in growth performance; therefore, the difference in feed cost when adding soybean meal or crystalline L-Trp to diet will be a major factor in choosing the optimal source of Trp in diet formulation. The improvement in carcass yield also suggests an opportunity to increase carcass value with increasing Trp.

Key words: Dried distillers grains with solubles, tryptophan, tryptophan source

INTRODUCTION

Large neutral amino acids (LNAA) which include the branched-chain amino acid (Ile, Leu, and Val) and aromatic amino acid (Phe and Tyr) share a common transport system with Trp at intestine and blood-brain barrier (Henry and Seve, 1993). Thus, there is potential for competitive absorption when excesses of one or more of these amino acids are provided in the diet. It is hypothesized that the high level of LNAA in the diet will elevate the requirement for Trp because of decreased Trp utilization from the diet. A higher LNAA in diet has been reported to decrease growth performance at both adequate and sub-optimal Trp levels, with a large decrease observed at the low level of Trp (Henry, 1995; Henry et al., 1996). Accordingly, the interaction between LNAA and Trp raises the concern that optimal Trp level may be increased in diets with high inclusion rates of DDGS, because the corn protein in DDGS is low in Trp and high in LNAA. Nevertheless, only a few studies have investigated the Trp requirement in diet containing DDGS for grower-finisher pigs.

Salyer et al. (2013) observed a linear increase in ADG and ADFI as the SID Trp:Lys ratio increased through 19.5% of Lys in finishing pigs fed 30% DDGS using soybean meal as a source of Trp; however, the response was not replicated in the following trial (Nitikanchana et al., 2011a) that used crystalline L-Trp to increase the SID Trp:Lys ratio from 15 to 21%. These results suggest that Trp sources (crystalline L-Trp vs. soybean meal) may be important to obtain the growth response. Therefore, we conducted this experiment to evaluate Trp sources (crystalline L-Trp vs. soybean meal) used to increase the SID Trp:Lys ratio in diets containing 30% DDGS for finishing pigs from 71 to 127 kg.

MATERIALS AND METHODS

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. The studies were conducted at a commercial research-finishing barn in southwestern Minnesota. The barns were naturally ventilated and double-curtain-sided. Pens had completely slatted flooring and deep pits for manure storage. Each pen was equipped with a 5-hole stainless steel dry self-feeder and a cup waterer for ad libitum access to feed and water. Daily feed additions to each pen were accomplished through a robotic feeding system (FeedPro™; Feedlogic Corp., Willmar, MN) capable of providing and measuring feed amounts for individual pens.

Two replicated experiments were conducted using a total of 2,290 gilts (PIC 1050 × 337) with initial BW of 73 and 69 kg in Exp. 1 and 2, respectively, with 26 to 28 gilts per pen and 10 to 13 pens per treatment. Pens of pigs were assigned to 1 of 7 dietary treatments in a completely randomized design while balancing for initial BW within study. Treatments were arranged as a 2

× 3 factorial with the main effects of Trp source (L-Trp or soybean meal) and SID Trp:Lys ratio (18, 20, and 22% of Lys) with the addition of a control diet that contained 16% SID Trp:Lys. Soybean meal and DDGS sources used in each experiment were analyzed for total amino acid content (Table 4.1; Ajinomoto Heartland LLC, Chicago, IL). These values along with standardized digestibility coefficients from NRC (1998) for soybean meal and Stein (2007) for DDGS were used in diet formulation for each experiment. The SID Trp:Lys ratio was increased by adding crystalline Trp to the control diet at the expense of corn or by replacing crystalline Lys and corn with soybean meal. All diets were fed in meal form and fed in 3 phases from 73 to 93, 93 to 109, and 109 to 123 kg BW in Exp.1, and 69 to 88, 88 to 111, and 111 to 130 kg in Exp. 2 (Tables 4.2 to 4.7). All diets contained 30% DDGS except diets fed in the last phase, in which DDGS level was lowered to 15% to reduce the negative impact on carcass fat quality and carcass yield. Diets in phase 3 also contained 10 ppm of Ractopamine HCl (Paylean; Elanco Animal Health, Greenfield, IN). Diet samples were collected from feeders during every phase and stored at -20ºC, then amino acid analysis was conducted on composite samples by Ajinomoto Heartland LLC.

Pens of pigs were weighed and feed disappearance was recorded at d 22, 40, and 56 in Exp. 1 and at d 21, 47, and 68 in Exp. 2 to determine ADG, ADFI, G:F, income over feed cost (IOFC), and g of SID Trp intake per kg of gain. The formulated SID Trp in each phase was used to calculate g of SID Trp intake by phase then the summation of SID Trp intake of all phases was divided with the overall BW gain to represent the g of SID Trp intake per kg of BW gain. On d 40 of Exp. 1 and d 47 of Exp. 2, the 5 heaviest pigs per pen were weighed and sold according to the farm's normal marketing procedure. At the end of the trial, pigs were individually tattooed by pen number to allow for carcass data collection. Pigs were transported to JBS Swift and Company

(Worthington, MN) for processing and carcass data collection. Hot carcass weights (HCW) were measured immediately after evisceration, and carcass criteria of backfat depth and loin depth were collected using an optical probe. Carcass yield percentage was calculated by dividing carcass weight at the plant with live weight at the plant as reported by the processor, and percentage lean was calculated by the processor using a proprietary equation that depended on backfat and loin depth.

Income over feed cost is a method to measure an economic value by assuming that other costs, such as utility and labor, are constant and the only variables are ADG, carcass yield, and feed usage. Income over feed cost was calculated by subtracting the feed cost per pig from the gross income per pig. Gross income per pig is the income from selling one pig that was calculated from the total weight gain multiplied with carcass yield and carcass price. In the economic calculations, the average 5-year (2008 to 2012) price of corn, soybean meal, DDGS, and carcass weight reported by USDA was utilized. Corn was valued at $195/tonne, soybean meal at $384/tonne, DDGS at $178/tonne, L-Lys HCl at $1,762/tonne, DL-Met at $3,304/tonne, Thr at $2,533/tonne, L-Trp at $26,432/tonne, Ractopamine HCl at $70/kg, Phytase at $4.2/kg, and carcass price at $1.66/kg carcass weight.

Statistical Analysis

The experimental data were analyzed using the MIXED procedure of SAS (SAS institute, Inc., Cary, NC). Pen was the experimental unit for all data analysis, and experiment was included in the statistical model as a random effect. Analysis of backfat depth, loin depth, and percentage lean were adjusted to a common HCW. Contrast coefficients were used to evaluate linear and quadratic responses to SID Trp:Lys ratio (16, 18, 20, and 22%), to compare the two Trp sources (crystalline L-Trp vs. soybean meal), and to determine linear and quadratic SID Trp:Lys ratio by

Trp source interactions. Significance and tendencies were set at $P \leq 0.05$ and $P \leq 0.10$, respectively. Also, the second-order polynomial model was used to fit the response data, where the SID Trp:Lys ratios that gave the maximum response were determined by equalizing the first derivative to zero and then solving for the SID Trp:Lys ratio (Pesti et al., 2009).

RESULTS

The analyzed AA were within coefficient of variation between laboratories according to Cromwell et al. (1999) and within analytical variation for Lys content according to AAFCO (2013) except for Lys content of the 20% SID Trp:Lys ratio diet using soybean meal during phase 1 and 22% SID Trp:Lys ratio diet using crystalline L-Trp during phase 3 diets of Exp. 1 (Tables 4.8 to 4.13). Also, the analyzed total Trp content in the phase 1 diet with 20% SID Trp:Lys from soybean meal in Exp. 1 and the 22% SID Trp:Lys ratio from soybean meal in phase 3 diet of Exp. 2 were lower than expected.

During phase 1, a linear interaction ($P = 0.04$; Table 4.14) occurred between Trp source and SID Trp:Lys ratio for G:F. This was a result of an improvement in G:F (linear, $P < 0.01$; Table 4.14) when SID Trp:Lys ratio was increased using soybean meal while the best G:F (quadratic, $P = 0.13$) was achieved at 18% SID Trp:Lys when using crystalline L-Trp. An interaction in ADG (quadratic, $P = 0.02$) and ADFI (quadratic, $P = 0.01$) was observed during phase 2 due to the difference in pattern of response between sources. For pigs fed supplemental crystalline L-Trp, the greatest ADG and ADFI was for pigs fed 20% with a slight decrease at 22%, whereas pigs fed with soybean meal also had the greatest response at 20% but the response was numerically decreased at 22%. No interaction was detected ($P > 0.22$) during phase 3 when Ractopamine HCl was included in the diets. For the overall period (d 0 to market), an interaction (linear, $P = 0.03$) occurred between Trp source and SID Trp:Lys ratio for G:F. Increasing the SID Trp:Lys ratio improved (quadratic, $P < 0.01$) G:F, with the best G:F observed at 18% of SID Lys when crystalline L-Trp was a source of Trp and 20% of Lys when soybean meal was the source. A tendency for an interaction was also observed in g SID Trp intake for a kg gain (linear, $P = 0.07$); however, increasing SID Trp:Lys resulted in increased (quadratic, $P < 0.03$) g SID Trp intake for a kg gain in both Trp sources. For carcass characteristics, increasing the SID Trp:Lys ratio increased (linear, $P = 0.01$; Table 4.14) carcass yield when using crystalline L-Trp as a Trp source; however, the greatest yield was observed (quadratic, $P = 0.03$) at an 18% SID Trp:Lys ratio when adding soybean meal resulting in a Trp source by SID Trp:Lys ratio interaction (linear, $P = 0.01$). A tendency for an interaction was also observed in loin depth (quadratic, $P = 0.08$) and lean percentage (quadratic, $P = 0.07$). Increasing SID Trp:Lys ratio with crystalline L-Trp decreased loin depth (quadratic, $P < 0.01$) and lean percentage at 18% SID Trp:Lys, but no differences ($P > 0.11$) occurred when increasing Trp with soybean meal.

For the main effects, as the SID Trp:Lys ratio increased, ADG tended to improve (quadratic, $P = 0.10$; Table 4.15) during phase 1. Feed efficiency improved (linear, $P = 0.04$) when the SID Trp:Lys ratio increased, but ADFI was unaffected ($P > 0.41$). During phase 2, increasing the SID Trp:Lys ratio resulted in an increase in ADG (quadratic, $P = 0.09$) and ADFI (linear, $P < 0.01$), but did not affect G:F ($P > 0.16$). The greatest ADG and ADFI were observed at the 20% SID Trp:Lys ratio. During phase 3 when Ractopamine HCl was added to diets, ADG increased (quadratic, $P = 0.01$) and G:F improved (quadratic, $P < 0.01$) up to a 20% SID Trp:Lys ratio. For the overall period (d 0 to market), ADG and G:F improved (quadratic, $P < 0.01$) with the increasing SID Trp:Lys ratio, but with no differences in ADFI ($P > 0.44$). The greatest ADG and G:F for the overall period were also observed at the 20% SID Trp:Lys ratio. Fitting the overall responses to the second-order polynomial models revealed the maximum ADG at 19.5% SID Trp:Lys ratio and maximum G:F at 19.0% SID Trp:Lys when crystalline L-Trp was the source. Whereas the maximum ADG and G:F were determined at slightly greater SID Trp:Lys ratios of 19.8 and 19.9%, respectively, with soybean meal as the source of Trp. For carcass characteristics, pigs fed the 20% SID Trp:Lys ratio had the heaviest (quadratic, $P = 0.01$) HCW. Loin depth was greatest in the control diet (16% SID Trp:Lys ratio) and was lowest in the pigs fed 18% SID Trp:Lys ratio (quadratic, $P = 0.02$). Other carcass characteristics were unaffected ($P > 0.13$) by increasing the SID Trp:Lys ratio. Pigs fed 18% SID Trp:Lys ratio had the greatest IOFC for the overall period with a similar IOFC observed when SID Trp:Lys ratio was increased to 20% (quadratic, $P = 0.01$).

For the main effect of Trp source, growth performance during phase 1 did not differ ($P > 0.43$; Table 4.16) between pigs fed the two sources of Trp. During phase 2, pigs fed diets with soybean meal as a source of Trp had greater ADG ($P = 0.04$) than those fed diets with crystalline L-Trp as the source; however, there were no differences ($P > 0.23$) in ADFI or G:F. During phase 3, ADFI was greater ($P = 0.02$) when using crystalline L-Trp as a source of Trp compared with using soybean meal. However, ADG and G:F ($P > 0.11$) did not differ between pigs fed the two sources of Trp. For the overall period, a tendency was observed toward greater ADG ($P = 0.07$) when using soybean meal as a Trp source. For carcass characteristics, backfat depth was greater ($P = 0.04$) and percentage of lean was lower ($P = 0.02$) in pigs fed with crystalline L-Trp as the Trp source, but no difference in other carcass characteristics was detected. Income over feed cost was similar ($P = 0.42$) between pigs fed the two sources of Trp.

DISCUSSION

In this study, increasing the SID Trp:Lys ratio from 16 to 22% quadratically improved ADG with the best ADG was observed at 20% SID Trp:Lys ratio regardless of the source of Trp. The best feed efficiency was also observed at 20% SID Trp:Lys with using soybean meal as a source. However, when crystalline L-Trp was the Trp source, feeding at 18% SID Trp:Lys ratio appeared to result in the best feed efficiency. Nevertheless, there was no difference in feed efficiency between feeding at 18 or 20% SID Trp:Lys ratio in phase 2 and 3. Fitting the second-order polynomial models also showed the maximum growth responses near 20% SID Trp:Lys ratio. Therefore, this study suggests a 20% SID Trp:Lys ratio requirement for pigs from 71- to 127-kg BW.

Only a few studies have investigated the Trp requirement in for pigs fed diets containing DDGS. Hinson et al. (2010) increased SID Trp:Lys ratio from 12 to 20% with crystalline L-Trp and concluded a 16% SID Trp:Lys ratio to be optimal for 27- to 117-kg pigs fed 30% DDGS diet. In the study by Ma et al. (2010), 0.14, 0.11, and 0.11% SID Trp were determined as the requirement for barrows from 46 to 64, 70 to 93, and 95 to 115 kg, respectively, when fed diets with high protein distillers dried grains. Salyer et al. (2013) conducted two experiments titrating the SID Trp:Lys ratio from 14 to 18% and 15 to 19.5% in 30% DDGS diet with using soybean meal as the source of Trp. They concluded a requirement of 16.5% SID Trp:Lys for 36- to 70-kg pigs and a requirement of greater than 19.5% for pigs from 70- to 130-kg BW. The results of Salyer et al. (2013) and Hinson et al. (2010) agreed that 16 to 16.5% SID Trp:Lys ratio was optimal for pigs less than 70 kg when fed 30% DDGS diet. Nevertheless, the data from Ma et al. (2010) indicated a considerably lower SID Trp requirement when related to the SID Lys used in their study compared at similar BW range. It is notable that the SID Lys levels used in Ma et al. (2010) study (0.95, 0.81 and 0.73%) were significantly higher than the recommendation by NRC (2012) for barrows (0.81, 0.69, and 0.58% for 50 to 75, 75 to 100, and 100 to 135 kg, respectively). Therefore, it was possible that the Lys was over the requirement and such that the resulting SID Trp:Lys ratios were underestimated if Lys would have been fed closer to the requirement. This would also explain the lower requirement estimate in Ma et al. (2010) study for pigs greater than 70 kg comparing to the 20% SID Trp:Lys ratio requirement observed in our studies which agreed with the results from Salyer et al. (2013).

The present data indicates a higher SID Trp:Lys requirement than the current NRC (2012) suggestion of 18%, and also greater than the requirement observed in corn and non-corn based diet in several studies for similar BW range (Eder et al., 2003; Guzik et al., 2005; Kendall et al., 2007). Also, the amount of SID Trp for a kg of gain at the maximum growth (20% SID Trp:Lys) was observed at 4.6 g in this study which is significantly higher than the values (3.4 to 3.5 g) estimated in Eder et al. (2003) and Guzik et al. (2005) studies reported in NRC (2012) for pigs at similar BW. This higher Trp requirement in DDGS containing diets may be explained by an interaction between Trp and LNAA. The nutrients reported in NRC (2012) showed that the amount of Trp as a ratio to LNAA in DDGS (1.6 to 2.3%) is lower than in corn (2.5%), soybean meal (5.7%), wheat (5.7 – 6.0%), or barley (5.5%). Thus, the inclusion of dietary DDGS would increase the amount of LNAA that competes with Trp for absorption. This interaction was hypothesized to elevate the requirement of Trp in diets with high inclusion rates of DDGS.

Only a few experiments investigated the effect of increasing Trp on carcass characteristics. Our finding of an improvement in carcass yield with increasing Trp agreed with the results from our previous studies (Nitikanchana et al., 2011b, 2011c) and the data from Guzik et al. (2005). In the previous studies, we observed a linear improvement in carcass yield with increasing SID Trp:Lys ratio from 15 to 21% in diets with 30% DDGS and the tendency of interactions for carcass yield and percentage lean which indicated an advantage to increasing the SID Trp:Lys ratio (16 to 20%) in diets with high levels of DDGS (20 and 40%) compared with no advantage to increasing the ratio in the corn-soybean meal diet. Guzik et al. (2005) observed a linear improvement in carcass yield along with increased kilogram of carcass fat free lean when TID Trp was increased from 0.06 to 0.14% in corn-feather meal diets. Salyer et al. (2013) found a tendency of an improvement in fat free lean index (FFLI) along with a decreased backfat depth when they increased SID Trp:Lys ratio from 15 to 19.5% in 30% DDGS diets. Mohn and Susenbeth (1994) also demonstrated a linear improvement in percentage lean when increasing total Trp from 0.10 to 0.18% in a corn-pea-barley diet. From the results of these trials, it is evident that increasing Trp in diet provides an opportunity to improve carcass yield and lean percentage. There appears to be inconsistency in this response as some trials showed responses in both carcass yield and lean percentage, whereas others found responses in only one of the carcass traits. The variation between trials in genetic backgrounds that corresponds to the difference in lean deposition rate or the varying diet composition may explain the discrepancy. Also, in contrast to growth, carcass responses to increasing Trp in most studies (Mohn and Susenbeth, 1994; Guzik et al., 2005; Nitikanchana et al., 2011c) did not reach plateau even with the highest Trp content that were used, suggesting a higher Trp content to maximize carcass value compared to the level for maximum growth. These observations agreed with the study by Guzik et al. (2005) that showed a greater Trp requirement for carcass fat free lean than the requirement for growth rate or feed efficiency.

The quadratic improvement in ADG and G:F with increasing Trp demonstrated a diminishing rate of return in growth as SID Trp:Lys increased to 20% (Figures 4.1 and 4.2). Economic evaluation is; therefore, important to determine the optimal Trp in the diet to achieve maximum profit. Feeding at 18% SID Trp:Lys with soybean meal or 20% SID Trp:Lys with crystalline L-Trp only led to a 4 to 6% reduction in IOFC while up to a 14% reduction was observed with feeding outside this range (Figure 4.3). It is important to note that the average prices of corn, soybean meal, DDGS, and carcass weight from 2008 to 2012 was used in this IOFC calculation. We recognize that revenue price, feed ingredient values, and crystalline amino acid cost change over time and depend on location. Thus, the optimal Trp feeding level is dynamic and will require periodic economic re-evaluation.

Using crystalline L-Trp or soybean meal as a source of Trp yielded similar SID Trp:Lys ratio requirement and growth performances; thus, the difference in feed cost when adding soybean meal or crystalline L-Trp to the diet will be a major factor in choosing the optimal source of Trp in diet formulation. Although, in our study, growth performance was not impaired with fortifying crystalline L-Trp and other amino acids in the diet, the reduced carcass leanness that was observed may reduce carcass value.

In summary, the present data indicated an optimum SID Trp:Lys ratio of 20% for 71- to 127-kg BW pigs fed high levels of DDGS. Using soybean meal or crystalline L-Trp provided a similar response in growth performance; therefore, the economics will be a major factor in choosing the optimal source of Trp. The finding of an improvement in carcass yield also suggests an opportunity to increase carcass value with increasing Trp in diets with high inclusion rate of DDGS.

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FIGURES AND TABLES

Table 4.1 Amino acid analysis of soybean meal and dried distillers grains with solubles (DDGS)[1]

	Exp. 1		Exp. 2	
Total AA, %	Soybean meal	DDGS	Soybean meal	DDGS
Lys	2.81	0.86	2.74	0.86
Ile	1.99	0.91	1.88	0.90
Leu	3.30	2.86	3.18	2.76
Met	0.59	0.51	0.57	0.49
Cys	0.63	0.49	0.63	0.46
Met & Cys	1.22	1.00	1.21	0.95
Thr	1.78	1.00	1.70	0.95
Trp	0.64	0.25	0.58	0.22
Val	1.99	1.23	1.86	1.15

[1]Soybean meal and dried distillers grains with solubles (DDGS) were analyzed for total AA content by Ajinomoto Heartland LLC (Chicago, IL). These values along with standardized digestibility coefficients from NRC (1998) for soybean meal and Stein (2007) for DDGS were used in diet formulation for each study.

Table 4.2 Composition of diets (Exp. 1, phase 1, 73 to 93 kg; as-fed basis)[1]

		Trp source[2]	
Item	Control diet[3]	Crystalline L-Trp	Soybean meal
Ingredient, %			
Corn	60.30	60.30	57.55–51.91
Soybean meal	7.35	7.35	10.40
DDGS[4]	30.00	30.00	30.00
Limestone	1.25	1.78	1.15–1.10
Salt	0.35	0.35	0.35
Vitamin–trace mineral premix[5]	0.09	0.09	0.09
L-Lys sulfate	0.635	0.635	0.485–0.185
L-Trp	---	0.016	---
Phytase[6]	0.01	0.01	0.01
TOTAL	100	100	100
Calculated analysis			
Standadized ileal digestible (SID) amino acids,%			
Lys	0.79	0.79	0.78
Ile:Lys	61	61	68–74
Leu:Lys	188	188	197–216
Met:Lys	33	33	34–48
Met & Cys:Lys	66	66	69–76
Thr:Lys	60	60	65–76
Trp:Lys	16.0	18.0–22.0	18.0–22.0
Val:Lys	78	78	83–96
Phe:Lys	88	88	95–111
Tyr:Lys	63	63	69–81
Trp:LNAA[7]	3.3	3.8–4.6	3.5–3.8
Trp:BCAA[8]	4.9	5.5–6.7	5.2–5.7
Total Lys, %	0.94	0.94	0.94–0.95
ME, kcal/kg	3,361	3,361	3,361
SID Lys:ME, g/Mcal	2.35	2.35	2.32
CP, %	17.2	17.2	19.3
Ca, %	0.50	0.50	0.50
P, %	0.43	0.43	0.46
Available P, %	0.20	0.20	0.21

[1] Phase 1 diet of Exp.1 was fed from 73- to 93-kg BW. Corn and soybean meal were analyzed for total amino acid content and used in the diet formulation.

[2] Crystalline L-Trp was added at 0.016, 0.032, and 0.048% to the control diet at the expense of corn to provide SID Trp:Lys ratios of 18, 20, and 22%. Soybean meal replaced corn and crystalline Lys in the control diet for total soybean meal levels of 10.40, 13.37, and 16.38% to achieve SID Trp:Lys ratios of 18, 20, and 22%.

[3] Control diet was formulated to 16% SID Trp:Lys ratio.

[4] Dried distillers grains with solubles from Valero (Aurora, SD).

[5] Provided per kg of premix: 4,509,409 IU vitamin A; 701,464 IU vitamin D3; 24,050 IU vitamin E; 1,402 mg vitamin K; 12,025 pantothenic acid; 18,037 mg niacin; 3,006 mg vitamin B2 and 15,031 mg vitamin B12, 40,084 mg Mn from manganese oxide, 90,188 mg Fe from iron sulfate, 100,209 Zn from zinc oxide, 10,021 mg Cu from copper sulfate, 501 mg I from Ethylenediamin dihydroiodide, and 300 mg Se from sodium selenite.

[6] OptiPhos 2000 (Enzyvia LLC, Sheridan, IN) provided 500 FTU per kg of diet.

[7] Amount of Trp in the diet as a ratio to large neutral AA (LNAA; Ile, Leu, Val, Phe, and Tyr) on SID basis. The ratios were 3.8, 4.2, 4.6, and 3.5, 3.7, 3.8 % as increasing SID Trp:Lys from 18, 20, to 22% with crystalline L-Trp and soybean meal, respectively.

[8] Amount of Trp in the diet as a ratio to branched-chain AA (BCAA; Ile, Leu, Val) on SID basis. The ratios were 5.5, 6.1, 6.7, and 5.2, 5.5, 5.7 % as increasing SID Trp:Lys from 18, 20, to 22% with crystalline L-Trp and soybean meal, respectively.

Table 4.3 Composition of diets (Exp.1, phase 2, 93 to 109 kg; as-fed basis)[1]

		Trp source[2]	
Item	Control diet[3]	Crystalline L-Trp	Soybean meal
Ingredient, %			
Corn	64.95	64.95	62.60–57.99
Soybean meal	2.80	2.80	5.30
DDGS[4]	30.00	30.00	30.00
Limestone	1.23	1.23	1.20–1.15
Salt	0.35	0.35	0.35
Vitamin–trace mineral premix[5]	0.09	0.09	0.09
L-Lys sulfate	0.545	0.545	0.430–0.205
L-Thr	0.005	0.005	---
L-Trp	---	0.013	---
Phytase[6]	0.01	0.01	0.01
TOTAL	100	100	100
Calculated analysis			
Standadized ileal digestible (SID) amino acids, %			
Lys	0.64	0.64	0.64
Ile:Lys	65	65	71–83
Leu:Lys	218	218	226–241
Met:Lys	38	38	39–42
Met & Cys:Lys	76	76	79–85
Thr:Lys	65	65	70–80
Trp:Lys	16.0	18.0–22.0	18.0–22.0
Val:Lys	86	86	91–102
Phe:Lys	96	96	103–117
Tyr:Lys	68	68	74–85
Trp:LNAA[7]	3.0	3.4–4.1	3.2–3.5
Trp:BCAA[8]	4.3	4.9–6.0	4.6–5.2
Total Lys, %	0.78	0.78	0.79–0.80
ME, kcal/kg	3,363	3,363	3,361
SID Lys:ME, g/Mcal	1.90	1.90	1.90
CP, %	15.4	15.4	17.1
Ca, %	0.50	0.50	0.50
P, %	0.42	0.42	0.44
Available P, %	0.19	0.19	0.20

[1] Phase 2 diet of Exp. 1 was fed from 93-to 109-kg BW. Corn and soybean meal were analyzed for total amino acid content and used in the diet formulation.

[2] Crystalline L-Trp was added at 0.013, 0.026, and 0.038% to the control diet at the expense of corn to provide SID Trp:Lys ratios of 18, 20, and 22%. Soybean meal replaced corn and crystalline Lys in the control diet for total soybean meal levels of 5.30, 7.70, and 10.20% to achieve SID Trp:Lys ratios of 18, 20, and 22%.

[3] Control diet was formulated to 16% SID Trp:Lys ratio.

[4] Dried distillers grains with solubles from Valero (Aurora, SD).

[5] Provided per kg of premix: 4,509,409 IU vitamin A; 701,464 IU vitamin D3; 24,050 IU vitamin E; 1,402 mg vitamin K; 12,025 pantothenic acid; 18,037 mg niacin; 3,006 mg vitamin B2 and 15,031 mg vitamin B12, 40,084 mg Mn from manganese oxide, 90,188 mg Fe from iron sulfate, 100,209 Zn from zinc oxide, 10,021 mg Cu from copper sulfate, 501 mg I from Ethylenediamin dihydroiodide, and 300 mg Se from sodium selenite.

[6] OptiPhos 2000 (Enzyvia LLC, Sheridan, IN) provided 500 FTU per kg of diet.

[7]Amount of Trp in the diet as a ratio to large neutral AA (LNAA; Ile, Leu, Val, Phe, and Tyr) on SID basis. The ratios were 3.4, 3.8, 4.1, and 3.2, 3.4, 3.5 % as increasing SID Trp:Lys from 18, 20, to 22% with crystalline L-Trp and soybean meal, respectively.

[8] Amount of Trp in the diet as a ratio to branched-chain AA (BCAA; Ile, Leu, Val) on SID basis. The ratios were 4.9, 5.4, 6.0, and 4.6, 4.9, 5.2 % as increasing SID Trp:Lys from 18, 20, to 22% with crystalline L-Trp and soybean meal, respectively.

Table 4.4 Composition of diets (Exp. 1, phase 3, 109 to 123 kg; as-fed basis)[1]

		Trp source[2]	
Item	Control diet[3]	Crystalline L-Trp	Soybean meal
Ingredient, %			
Corn	68.91	68.91	65.90–59.62
Soybean meal	13.70	13.70	16.95
DDGS[4]	15.00	15.00	15.00
Limestone	1.13	1.13	1.10–1.05
Salt	0.35	0.35	0.35
Vitamin–trace mineral premix[5]	0.09	0.09	0.09
L-Lys sulfate	0.620	0.620	0.470–0.160
L-Thr	0.115	0.115	0.075–0.03
Met hydroxy	0.040	0.040	0.010–0
L-Trp	---	0.018	---
Phytase[6]	0.01	0.01	0.01
Ractopamine HCl, 20 g/kg[7]	0.05	0.05	0.05
TOTAL	100	100	100
Calculated analysis			
Standadized ileal digestible (SID) amino acids, %			
Lys	0.88	0.88	0.88
Ile:Lys	59	59	64–76
Leu:Lys	158	158	166–181
Met:Lys	32	32	30–32
Met & Cys:Lys	60	60	60–65
Thr:Lys	68	68	68–70
Trp:Lys	16.0	18.0–22.0	18.0–22.0
Val:Lys	70	70	75–86
Phe:Lys	79	79	86–99
Tyr:Lys	57	57	62–73
Trp:LNAA[8]	3.8	4.3–5.2	4.0–4.3
Trp:BCAA[9]	5.6	6.3–7.7	5.9–6.4
Total Lys, %	1.01	1.01	1.01–1.03
ME, kcal/kg	3,361	3,363	3,357
SID Lys:ME, g/Mcal	2.62	2.61	2.62
CP, %	16.9	16.9	19.1
Ca, %	0.50	0.50	0.50
P, %	0.39	0.39	0.42
Available P, %	0.13	0.13	0.14

[1] Phase 3 diet of Exp. 1 was fed from 109- to 123-kg BW. Corn and soybean meal were analyzed for total amino acid content and used in the diet formulation.

[2] Crystalline L-Trp was added at 0.018, 0.036, and 0.054% to the control diet at the expense of corn to provide SID Trp:Lys ratios of 18, 20, and 22%. Soybean meal replaced corn and crystalline Lys in the control diet for total soybean meal levels of 16.95, 20.40, and 23.65% to achieve SID Trp:Lys ratios of 18, 20, and 22%.

[3] Control diet was formulated to 16% SID Trp:Lys ratio.

[4] Dried distillers grains with solubles from Valero (Aurora, SD).

[5] Provided per kg of premix: 4,509,409 IU vitamin A; 701,464 IU vitamin D3; 24,050 IU vitamin E; 1,402 mg vitamin K; 12,025 pantothenic acid; 18,037 mg niacin; 3,006 mg vitamin B2 and 15,031 mg vitamin B12, 40,084 mg Mn from manganese oxide, 90,188 mg Fe from iron sulfate, 100,209 Zn from zinc oxide, 10,021 mg Cu from copper sulfate, 501 mg I from Ethylenediamin dihydroiodide, and 300 mg Se from sodium selenite.

[6] OptiPhos 2000 (Enzyvia LLC, Sheridan, IN) provided 500 FTU per kg of diet.

[7] Ractopamine HCl (Paylean; Elanco Animal Health, Greenfield, IN) at 10 ppm was added.

[8] Amount of Trp in the diet as a ratio to large neutral AA (LNAA; Ile, Leu, Val, Phe, and Tyr) on SID basis. The ratios were 4.3, 4.7, 5.2, and 4.0, 4.1, 4.3 % as increasing SID Trp:Lys from 18, 20, to 22% with crystalline L-Trp and soybean meal, respectively.

[9] Amount of Trp in the diet as a ratio to branched-chain AA (BCAA; Ile, Leu, Val) on SID basis. The ratios were 6.3, 7.0, 7.7, and 5.9, 6.2, 6.4 % as increasing SID Trp:Lys from 18, 20, to 22% with L-Trp and soybean meal, respectively.

Table 4.5 Composition of diets (Exp. 2, phase 1, 69 to 88 kg; as-fed basis)[1]

		Trp source[2]	
Item	Control diet[3]	Crystalline L-Trp	Soybean meal
Ingredient, %			
Corn	58.07	58.07	54.80–48.45
Soybean meal	9.77	9.77	13.23
DDGS[4]	30.00	30.00	30.00
Limestone	1.17	1.17	1.14–1.09
Salt	0.35	0.35	0.35
Vitamin–trace mineral premix[5]	0.09	0.09	0.09
L-Lys sulfate	0.535	0.535	0.380–0.080
L-Trp	---	0.017	---
Phytase[6]	0.01	0.01	0.01
TOTAL	100	100	100
Calculated analysis			
Standadized ileal digestible (SID) amino acids, %			
Lys	0.79	0.79	0.79
Ile:Lys	65	65	71–83
Leu:Lys	190	190	198–215
Met:Lys	33	33	35–38
Met & Cys:Lys	66	66	69–76
Thr:Lys	62	62	67–77
Trp:Lys	16.0	18.0–22.0	18.0–22.0
Val:Lys	78	78	84–95
Phe:Lys	93	93	101–116
Tyr:Lys	68	68	74–86
Trp:LNAA[7]	3.2	3.7–4.5	3.4–3.7
Trp:BCAA[8]	4.8	5.4–6.6	5.1–5.6
Total Lys, %	0.95	0.95	0.94–0.97
ME, kcal/kg	3,361	3,363	3,359
SID Lysine:ME, g/Mcal	2.35	2.35	2.32
CP, %	18.0	18.1	20.4
Ca, %	0.50	0.50	0.50
P, %	0.44	0.44	0.47
Available P, %	0.20	0.20	0.21

[1] Phase 1 diet of Exp.1 was fed from 69- to 88-kg BW. Corn and SBM were analyzed for total amino acid content and used in the diet formulation.

[2] Crystalline L-Trp was added at 0.017, 0.033, and 0.049% to the control diet at the expense of corn to provide SID Trp:Lys ratios of 18, 20, and 22%. Soybean meal replaced corn and crystalline Lys in the control diet for total soybean meal levels of 13.23, 16.58, and 19.93% to achieve SID Trp:Lys ratios of 18, 20, and 22%.

[3] Control diet was formulated to 16% SID Trp:Lys ratio.

[4] Dried distillers grains with solubles from Valero (Aurora, SD).

[5] Provided per kg of premix: 4,509,409 IU vitamin A; 701,464 IU vitamin D3; 24,050 IU vitamin E; 1,402 mg vitamin K; 12,025 pantothenic acid; 18,037 mg niacin; 3,006 mg vitamin B2 and 15,031 mg vitamin B12, 40,084 mg Mn from manganese oxide, 90,188 mg Fe from iron sulfate, 100,209 Zn from zinc oxide, 10,021 mg Cu from copper sulfate, 501 mg I from Ethylenediamin dihydroiodide, and 300 mg Se from sodium selenite.

[6] OptiPhos 2000 (Enzyvia LLC, Sheridan, IN) provided 500 FTU per kg of diet.

[7] Amount of Trp in the diet as a ratio to large neutral AA (LNAA; Ile, Leu, Val, Phe, and Tyr) on SID basis. The ratios were 3.7, 4.1, 4.5, and 3.4, 3.6, 3.7 % as increasing SID Trp:Lys from 18, 20, to 22% with crystalline L-Trp and soybean meal, respectively.

[8] Amount of Trp in the diet as a ratio to branched-chain AA (BCAA; Ile, Leu, Val) on SID basis. The ratios were 5.4, 6.0, 6.6, and 5.1, 5.4, 5.6 % as increasing SID Trp:Lys from 18, 20, to 22% with crystalline L-Trp and soybean meal, respectively.

Table 4.6 Composition of diets (Exp. 2, phase 2, 88 to 111 kg; as-fed basis)[1]

Item	Control diet[3]	Trp source[2]	
		Crystalline L-Trp	Soybean meal
Ingredient, %			
Corn	63.18	63.16	60.54–55.37
Soybean meal	4.70	4.70	7.49
DDGS[4]	30.00	30.00	30.00
Limestone	1.20	1.20	1.18–1.13
Salt	0.35	0.35	0.35
Vitamin–trace mineral premix[5]	0.09	0.09	0.09
L-Lys sulfate	0.465	0.465	0.340–0.095
L-Trp	---	0.013	---
Phytase[6]	0.01	0.01	0.01
TOTAL	100	100	100
Calculated analysis			
Standadized ileal digestible (SID) amino acids, %			
Lys	0.64	0.64	0.64
Ile:Lys	68	68	75–87
Leu:Lys	219	219	22–244
Met:Lys	38	38	40–43
Met & Cys:Lys	76	76	79–85
Thr:Lys	66	66	72–82
Trp:Lys	16.0	18.0–22.0	18.0–22.0
Val:Lys	86	86	92–103
Phe:Lys	101	101	109–124
Tyr:Lys	72	72	79–81
Trp:LNAA[7]	2.9	3.3–4.0	3.1–3.4
Trp:BCAA[8]	4.3	4.8–5.9	4.6–5.1
Total Lys, %	0.79	0.79	0.79–0.80
ME, kcal/kg	3,363	3,363	3,359
SID Lys:ME, g/Mcal	1.90	1.90	1.90
CP, %	16.1	16.1	18.0
Ca, %	0.50	0.50	0.50
P, %	0.42	0.42	0.45
Available P, %	0.20	0.20	0.20

[1] Phase 2 diet of Exp.2 was fed from 88- to 111-kg BW. Corn and soybean meal were analyzed for total amino acid content and used in the diet formulation.

[2] Crystalline L-Trp was added at 0.013, 0.026, and 0.039% to the control diet at the expense of corn to provide SID Trp:Lys ratios of 18, 20, and 22%. Soybean meal replaced corn and crystalline Lys in the control diet for total soybean meal levels of 7.49, 10.17, and 12.96% to achieve SID Trp:Lys ratios of 18, 20, and 22%.

[3] Control diet was formulated to 16% SID Trp:Lys ratio.

[4] Dried distillers grains with solubles from Valero (Aurora, SD).

[5] Provided per kg of premix: 4,509,409 IU vitamin A; 701,464 IU vitamin D3; 24,050 IU vitamin E; 1,402 mg vitamin K; 12,025 pantothenic acid; 18,037 mg niacin; 3,006 mg vitamin B2 and 15,031 mg vitamin B12, 40,084 mg Mn from manganese oxide, 90,188 mg Fe from iron sulfate, 100,209 Zn from zinc oxide, 10,021 mg Cu from copper sulfate, 501 mg I from Ethylenediamin dihydroiodide, and 300 mg Se from sodium selenite.

[6] OptiPhos 2000 (Enzyvia LLC, Sheridan, IN) provided 500 FTU per kg of diet.

[7] Amount of Trp in the diet as a ratio to large neutral AA (LNAA; Ile, Leu, Val, Phe, and Tyr) on SID basis. The ratios were 3.3, 3.7, 4.0, and 3.1, 3.2, 3.4 % as increasing SID Trp:Lys from 18, 20, to 22% with crystalline L-Trp and soybean meal, respectively.

[8] Amount of Trp in the diet as a ratio to branched-chain AA (BCAA; Ile, Leu, Val) on SID basis. The ratios were 4.8, 5.3, 5.9, and 4.6, 4.8, 5.1 % as increasing SID Trp:Lys from 18, 20, to 22% with crystalline L-Trp and soybean meal, respectively.

Table 4.7 Composition of diets (Exp. 2, phase 3, 111 to 130 kg; as-fed basis)[1]

		Trp source[2]	
Item	Control diet[3]	Crystalline L-Trp	Soybean meal
Ingredient, %			
Corn	66.65	66.63	63.14–56.00
Soybean meal	16.08	16.08	19.87
DDGS[4]	15.00	15.00	15.00
Limestone	1.10	1.10	1.08–1.03
Salt	0.5	0.35	0.35
Vitamin–trace mineral premix[5]	0.09	0.09	0.09
L-Lys sulfate	0.530	0.530	0.360–0.020
L-Thr	0.100	0.100	0.005–0.00
Met hydroxy	0.040	0.040	0.010–0
L-Trp	---	0.018	---
Phytase[6]	0.01	0.01	0.01
Ractopamine HCl, 20 g/kg[7]	0.05	0.05	0.05
TOTAL	100	100	100
Calculated analysis			
Standadized ileal digestible (SID) amino acids, %			
Lys	0.88	0.88	0.88
Ile:Lys	61	61	67–79
Leu:Lys	160	160	169–186
Met:Lys	32	32	31–33
Met & Cys:Lys	61	61	61–67
Thr:Lys	68	68	68–73
Trp:Lys	16.0	18.0–22.0	18.0–22.0
Val:Lys	71	71	76–87
Phe:Lys	84	84	92–107
Tyr:Lys	61	61	67–79
Trp:LNAA[8]	3.7	4.1–5.0	3.8–4.1
Trp:BCAA[9]	5.5	6.2–7.5	5.8–6.3
Total Lys, %	1.01	1.01	1.02–1.04
ME, kcal/kg	3,361	3,361	3,357
SID Lys:ME, g/Mcal	2.62	2.61	2.62
CP, %	17.7	17.7	20.3
Ca, %	0.50	0.50	0.50
P, %	0.40	0.40	0.44

Available P, %	0.13	0.13	0.14

[1] Phase 3 diet of Exp. 1 was fed from 111- to 130-kg BW. Corn and soybean meal were analyzed for total amino acid content and used in the diet formulation.

[2] Crystalline L-Trp was added at 0.018, 0.036, and 0.054% to the control diet at the expense of corn to provide SID Trp:Lys ratios of 18, 20, and 22%. Soybean meal replaced corn and crystalline Lys in the control diet for total soybean meal levels of 19.87, 23.66, and 27.46% to achieve SID Trp:Lys ratios of 18, 20, and 22%.

[3] Control diet was formulated to 16% SID Trp:Lys ratio.

[4] Dried distillers grains with solubles from Valero (Aurora, SD).

[5] Provided per kg of premix: 4,509,409 IU vitamin A; 701,464 IU vitamin D3; 24,050 IU vitamin E; 1,402 mg vitamin K; 12,025 pantothenic acid; 18,037 mg niacin; 3,006 mg vitamin B2 and 15,031 mg vitamin B12, 40,084 mg Mn from manganese oxide, 90,188 mg Fe from iron sulfate, 100,209 Zn from zinc oxide, 10,021 mg Cu from copper sulfate, 501 mg I from Ethylenediamin dihydroiodide, and 300 mg Se from sodium selenite.

[6] OptiPhos 2000 (Enzyvia LLC, Sheridan, IN) provided 500 FTU per kg of diet.

[7] Ractopamine HCl (Paylean; Elanco Animal Health, Greenfield, IN) at 10 ppm was added.

[8] Amount of Trp in the diet as a ratio to large neutral AA (LNAA; Ile, Leu, Val, Phe, and Tyr) on SID basis. The ratios were 4.1, 4.6, 5.0, and 3.8, 4.0, 4.1 % as increasing SID Trp:Lys from 18, 20, to 22% with L-tryptophan and SBM, respectively.

[9] Amount of Trp in the diet as a ratio to branched-chain AA (BCAA; Ile, Leu, Val) on SID basis. The ratios were 6.2, 6.9, 7.5, and 5.8, 6.0, 6.3 % as increasing SID Trp:Lys from 18, 20, to 22% with crystalline L-Trp and soybean meal, respectively.

Table 4.8 Total amino acid (AA) analysis of diets (Exp. 1, phase 1)[1]

Trp source:	Control	Crystalline L-Trp			Soybean meal		
SID Trp:Lys:	16.0	18.0	20.0	22.0	18.0	20.0	22.0
Total AA, %							
Lys	0.91 (0.94)[2]	0.91 (0.94)	0.88 (0.94)	0.87 (0.94)	0.88 (0.94)	0.72 (0.95)	0.84 (0.95)
Free Lys	0.46 (0.32)	0.40 (0.32)	0.41 (0.32)	0.38 (0.32)	0.30 (0.25)	0.22 (0.17)	0.15 (0.09)
Ile	0.61 (0.59)	0.64 (0.59)	0.63 (0.59)	0.62 (0.59)	0.63 (0.64)	0.50 (0.69)	0.73 (0.75)
Leu	1.52 (1.70)	1.58 (1.70)	1.53 (1.70)	1.54 (1.70)	1.57 (1.77)	1.34 (1.84)	1.67 (1.91)
Met	0.26 (0.30)	0.27 (0.30)	0.26 (0.30)	0.27 (0.30)	0.28 (0.31)	0.26 (0.33)	0.30 (0.34)
Cys	0.25 (0.31)	0.26 (0.31)	0.25 (0.31)	0.26 (0.31)	0.29 (0.32)	0.28 (0.34)	0.31 (0.35)
Thr	0.55 (0.61)	0.56 (0.61)	0.54 (0.61)	0.57 (0.61)	0.61 (0.65)	0.54 (0.70)	0.65 (0.74)
Trp	0.141 (0.159)	0.151 (0.175)	0.158 (0.191)	0.164 (0.207)	0.164 (0.177)	0.135 (0.194)	0.168 (0.211)
Free Trp	0.004 (---)	0.010 (0.016)	0.020 (0.032)	0.026 (0.047)	0.004 (---)	0.005 (---)	0.007 (---)
Val	0.73 (0.76)	0.76 (0.76)	0.75 (0.76)	0.75 (0.76)	0.78 (0.80)	0.67 (0.85)	0.84 (0.90)

[1] Diet samples were collected from feeders and stored at -20ºC, then total AA analysis was conducted on composite samples by Ajinomoto Heartland LLC (Chicago, IL).

[2] Values in parentheses indicate formulated values.

Table 4.9 Total amino acid (AA) analysis of diets (Exp. 1, phase 2)[1]

Trp source:	Control	Crystalline L-Trp			Soybean meal		
SID Trp:Lys:	16.0	18.0	20.0	22.0	18.0	20.0	22.0
Total AA, %							
Lys	0.64 (0.78)[2]	0.87 (0.78)	0.84 (0.78)	0.88 (0.78)	0.83 (0.79)	0.85 (0.79)	0.80 (0.80)
Free Lys	0.30 (0.28)	0.40 (0.28)	0.34 (0.28)	0.34 (0.28)	0.30 (0.22)	0.19 (0.16)	0.13 (0.10)
Ile	0.41 (0.51)	0.61 (0.51)	0.62 (0.51)	0.60 (0.51)	0.60 (0.56)	0.67 (0.60)	0.70 (0.64)
Leu	1.22 (1.60)	1.47 (1.60)	1.42 (1.60)	1.40 (1.60)	1.33 (1.66)	1.44 (1.71)	1.54 (1.77)
Met	0.23 (0.28)	0.25 (0.28)	0.25 (0.28)	0.25 (0.28)	0.23 (0.29)	0.25 (0.30)	0.27 (0.31)
Cys	0.23 (0.29)	0.27 (0.29)	0.24 (0.29)	0.27 (0.29)	0.25 (0.30)	0.28 (0.31)	0.27 (0.32)
Thr	0.47 (0.55)	0.57 (0.55)	0.61 (0.55)	0.62 (0.55)	0.58 (0.58)	0.60 (0.61)	0.65 (0.65)
Trp	0.111 (0.133)	0.140 (0.146)	0.168 (0.158)	0.182 (0.171)	0.171 (0.147)	0.165 (0.161)	0.176 (0.176)
Free Trp	0.004 (---)	0.011 (0.013)	0.025 (0.026)	0.036 (0.038)	0.010 (---)	0.009 (---)	0.008 (---)
Val	0.61 (0.68)	0.64 (0.68)	0.72 (0.68)	0.70 (0.68)	0.69 (0.72)	0.75 (0.76)	0.78 (0.80)

[1] Diet samples were collected from feeders and stored at -20ºC, then total AA analysis was conducted on composite samples by Ajinomoto Heartland LLC (Chicago, IL).
[2] Values in parentheses indicate formulated values.

Table 4.10 Total amino acid (AA) analysis of diets (Exp. 1, phase 3)[1]

Trp source:	Control	Crystalline L-Trp			Soybean meal		
SID Trp:Lys:	16.0	18.0	20.0	22.0	18.0	20.0	22.0
Total AA, %							
Lys	0.76 (1.01)[2]	0.85 (1.01)	0.84 (1.01)	0.62 (1.01)	0.73 (1.01)	0.97 (1.02)	0.85 (1.03)
Free Lys	0.32 (0.31)	0.37 (0.31)	0.39 (0.31)	0.19 (0.31)	0.27 (0.24)	0.20 (0.16)	0.13 (0.08)
Ile	0.50 (0.60)	0.61 (0.60)	0.63 (0.60)	0.44 (0.60)	0.56 (0.66)	0.74 (0.72)	0.76 (0.78)
Leu	1.45 (1.57)	1.55 (1.57)	1.46 (1.57)	1.25 (1.57)	1.43 (1.64)	1.57 (1.72)	1.73 (1.80)
Met	0.26 (0.31)	0.25 (0.31)	0.25 (0.31)	0.24 (0.31)	0.26 (0.30)	0.28 (0.30)	0.30 (0.32)
Cys	0.25 (0.29)	0.24 (0.29)	0.25 (0.29)	0.23 (0.29)	0.24 (0.31)	0.30 (0.32)	0.30 (0.34)
Thr	0.54 (0.71)	0.57 (0.71)	0.63 (0.71)	0.51 (0.71)	0.51 (0.72)	0.66 (0.73)	0.68 (0.75)
Trp	0.133 (0.168)	0.148 (0.185)	0.167 (0.203)	0.160 (0.220)	0.124 (0.186)	0.178 (0.207)	0.185 (0.225)
Free Trp	0.005 (---)	0.011 (0.018)	0.020 (0.035)	0.039 (0.053)	0.006 (---)	0.007 (---)	0.008 (---)
Val	0.69 (0.73)	0.72 (0.73)	0.73 (0.73)	0.62 (0.73)	0.68 (0.78)	0.83 (0.84)	0.87 (0.89)

[1] Diet samples were collected from feeders and stored at -20ºC, then total AA analysis was conducted on composite samples by Ajinomoto Heartland LLC (Chicago, IL).
[2] Values in parentheses indicate formulated values.

Table 4.11 Total amino acid (AA) analysis of diets (Exp. 2, phase 1)[1]

Trp source:	Control	Crystalline L-Trp			Soybean meal		
SID Trp:Lys:	16.0	18.0	20.0	22.0	18.0	20.0	22.0
Total AA, %							
Lys	0.90 (0.95)[2]	0.90 (0.95)	0.95 (0.95)	0.90 (0.95)	0.85 (0.95)	0.89 (0.96)	1.03 (0.97)
Free Lys	0.25 (0.27)	0.23 (0.27)	0.29 (0.27)	0.26 (0.27)	0.18 (0.19)	0.11 (0.12)	0.03 (0.04)
Ile	0.63 (0.62)	0.63 (0.62)	0.60 (0.62)	0.58 (0.62)	0.63 (0.67)	0.69 (0.73)	0.79 (0.78)
Leu	1.64 (1.72)	1.62 (1.72)	1.55 (1.72)	1.55 (1.72)	1.58 (1.79)	1.69 (1.87)	1.65 (1.94)
Met	0.29 (0.30)	0.30 (0.30)	0.29 (0.30)	0.30 (0.30)	0.29 (0.32)	0.31 (0.33)	0.30 (0.34)
Cys	0.29 (0.31)	0.30 (0.31)	0.29 (0.31)	0.29 (0.31)	0.30 (0.33)	0.31 (0.34)	0.32 (0.36)
Thr	0.60 (0.62)	0.61 (0.62)	0.58 (0.62)	0.60 (0.62)	0.61 (0.67)	0.66 (0.72)	0.73 (0.76)
Trp	0.168 (0.157)	0.175 (0.173)	0.173 (0.189)	0.186 (0.205)	0.173 (0.175)	0.193 (0.192)	0.222 (0.209)
Free Trp	0.004 (---)	0.013 (0.016)	0.024 (0.032)	0.038 (0.048)	0.007 (---)	0.006 (---)	0.011 (---)
Val	0.80 (0.76)	0.79 (0.76)	0.75 (0.76)	0.73 (0.76)	0.79 (0.81)	0.83 (0.86)	0.90 (0.91)

[1] Diet samples were collected from feeders and stored at -20ºC, then total AA analysis was conducted on composite samples by Ajinomoto Heartland LLC (Chicago, IL).

[2] Values in parentheses indicate formulated values.

Table 4.12 Total amino acid (AA) analysis of diets (Exp.2, phase 2)[1]

Trp source:	Control	Crystalline L-Trp			Soybean meal		
SID Trp:Lys:	16.0	18.0	20.0	22.0	18.0	20.0	22.0
Total AA, %							
Lys	0.80 (0.79)[2]	0.72 (0.79)	0.78 (0.79)	0.76 (0.79)	0.76 (0.79)	0.74 (0.80)	0.82 (0.80)
Free Lys	0.23 (0.24)	0.22 (0.24)	0.24 (0.24)	0.27 (0.24)	0.18 (0.17)	0.12 (0.11)	0.07 (0.05)
Ile	0.49 (0.54)	0.53 (0.54)	0.54 (0.54)	0.45 (0.54)	0.55 (0.58)	0.58 (0.62)	0.65 (0.67)
Leu	1.48 (1.61)	1.45 (1.61)	1.47 (1.61)	1.31 (1.61)	1.47 (1.67)	1.53 (1.73)	1.62 (1.79)
Met	0.28 (0.28)	0.27 (0.28)	0.27 (0.28)	0.25 (0.28)	0.27 (0.29)	0.29 (0.30)	0.30 (0.32)
Cys	0.27 (0.29)	0.27 (0.29)	0.27 (0.29)	0.25 (0.29)	0.27 (0.30)	0.28 (0.31)	0.31 (0.32)
Thr	0.56 (0.55)	0.52 (0.55)	0.54 (0.55)	0.49 (0.55)	0.54 (0.59)	0.58 (0.63)	0.64 (0.67)
Trp	0.139 (0.131)	0.137 (0.143)	0.151 (0.156)	0.154 (0.169)	0.147 (0.145)	0.161 (0.159)	0.176 (0.173)
Free Trp	0.006 (---)	0.008 (0.013)	0.016 (0.026)	0.028 (0.038)	0.010 (---)	0.007 (---)	0.006 (---)
Val	0.68 (0.68)	0.68 (0.68)	0.69 (0.68)	0.63 (0.68)	0.70 (0.72)	0.73 (0.76)	0.79 (0.80)

[1] Diet samples were collected from feeders and stored at -20ºC, then total AA analysis was conducted on composite samples by Ajinomoto Heartland LLC (Chicago, IL).

[2] Values in parentheses indicate formulated values.

Table 4.13 Total amino acid (AA) analysis of diets (Exp.2, phase 3)[1]

Trp source:	Control	Crystalline L-Trp			Soybean meal		
SID Trp:Lys:	16.0	18.0	20.0	22.0	18.0	20.0	22.0
Total AA, %							
Lys	0.87 (1.01)[2]	0.87 (1.01)	0.93 (1.01)	0.97 (1.01)	0.93 (1.02)	0.96 (1.03)	0.94 (1.04)
Free Lys	0.20 (0.27)	0.26 (0.27)	0.25 (0.27)	0.26 (0.27)	0.22 (0.18)	0.10 (0.10)	0.18 (0.01)
Ile	0.55 (0.63)	0.59 (0.63)	0.56 (0.63)	0.60 (0.63)	0.60 (0.69)	0.66 (0.75)	0.67 (0.81)
Leu	1.34 (1.59)	1.38 (1.59)	1.35 (1.59)	1.45 (1.59)	1.54 (1.67)	1.51 (1.76)	1.71 (1.84)
Met	0.26 (0.32)	0.25 (0.32)	0.25 (0.32)	0.27 (0.32)	0.29 (0.30)	0.28 (0.31)	0.32 (0.33)
Cys	0.25 (0.30)	0.26 (0.30)	0.27 (0.30)	0.27 (0.30)	0.27 (0.31)	0.29 (0.33)	0.31 (0.35)
Thr	0.68 (0.71)	0.61 (0.71)	0.62 (0.71)	0.67 (0.71)	0.63 (0.71)	0.66 (0.72)	0.66 (0.77)
Trp	0.168 (0.166)	0.160 (0.184)	0.182 (0.202)	0.196 (0.219)	0.176 (0.186)	0.197 (0.205)	0.170 (0.225)
Free Trp	0.010 (---)	0.016 (0.018)	0.030 (0.035)	0.040 (0.053)	0.009 (---)	0.013 (---)	0.007 (---)
Val	0.72 (0.74)	0.72 (0.74)	0.69 (0.74)	0.71 (0.74)	0.73 (0.79)	0.77 (0.85)	0.84 (0.90)

[1] Diet samples were collected from feeders and stored at -20ºC, then total AA analysis was conducted on composite samples by Ajinomoto Heartland LLC (Chicago, IL).

[2] Values in parentheses indicate formulated values.

Table 4.14 . Effects of Trp sources to increasing SID Trp:Lys ratio in diets containing dried distillers grains with solubles (DDGS) on growth performance and carcass characteristics of finishing pigs[1]

Trp source:	Control	Crystalline L-Trp			Soybean Meal				Probability, *P* <					
									SID Trp:Lys × Trp source		Crystalline L-Trp[2]		Soybean meal	
SID Trp:Lys:	16.0	18.0	20.0	22.0	18.0	20.0	22.0	SEM	Linear	Quad	Linear	Quad	Linear	Quad
Replications	13	12	13	12	12	13	10							
Initial BW, kg	71.2	71.2	71.1	71.2	71.2	71.3	71.2	1.89	0.99	0.92	0.98	0.93	0.99	0.97
Final BW, kg	124.9	125.7	127.6	126.0	127.0	129.2	126.4	3.68	0.78	0.36	0.29	0.26	0.20	0.03
<u>Phase 1[3]</u>														
ADG, g	876	912	910	886	880	937	910	17.5	0.13	0.50	0.73	0.09	0.05	0.39
ADFI, g	2582	2513	2627	2525	2536	2595	2502	46.8	0.51	0.89	0.73	0.66	0.30	0.54
G:F	0.340	0.363	0.347	0.351	0.349	0.362	0.364	0.009	0.04	0.47	0.56	0.13	0.01	0.60
<u>Phase 2</u>														
ADG, g	851	833	885	872	875	925	866	27.2	0.78	0.02	0.08	0.86	0.16	0.01
ADFI, g	2861	2773	3015	3017	2946	3022	2947	82.5	0.05	0.01	0.01	0.24	0.07	0.05
G:F	0.297	0.301	0.293	0.289	0.298	0.306	0.294	0.005	0.23	0.65	0.15	0.40	0.91	0.17
<u>Phase 3</u>														
ADG, g	997	1045	1107	1005	1061	1081	1040	32.2	0.67	0.55	0.52	0.01	0.29	0.09
ADFI, g	3167	2969	3149	3015	3183	3140	3159	92.1	0.47	0.67	0.29	0.57	0.80	0.98
G:F	0.315	0.353	0.352	0.334	0.333	0.345	0.330	0.015	0.97	0.22	0.10	0.01	0.06	0.01

<u>Overall</u>														
ADG, g	897	915	948	908	926	968	928	11.7	0.21	0.70	0.17	0.01	0.01	0.01
ADFI, g	2834	2720	2897	2825	2847	2885	2835	34.7	0.51	0.20	0.30	0.52	0.78	0.35
G:F	0.317	0.337	0.327	0.322	0.326	0.336	0.327	0.003	0.03	0.30	0.68	0.01	0.01	0.01
SID Trp g/kg gain[4]	3.8	4.1	4.6	5.2	4.2	4.5	5.1	0.05	0.07	0.43	0.01	0.01	0.01	0.03
Carcass wt, kg	93.2	94.2	95.1	93.7	95.5	96.2	93.7	3.8	0.96	0.31	0.54	0.15	0.59	0.01
Carcass yield, %	74.3	75.4	74.7	75.8	75.8	74.6	74.6	0.61	0.01	0.08	0.01	0.99	0.86	0.03
Backfat[5], mm.	14.8	14.7	14.7	14.6	14.3	14.1	14.3	1.03	0.39	0.22	0.50	0.94	0.12	0.13
Loin depth, mm.	71.9	69.3	70.3	70.9	70.5	71.0	70.5	0.53	0.50	0.08	0.35	0.01	0.11	0.42
Lean, %	58.5	58.2	58.4	58.5	58.6	58.8	58.6	0.63	0.70	0.07	0.84	0.24	0.55	0.29
IOFC[6], $/pig	21.3	24.6	23.0	21.6	23.8	24.7	22.0	4.06	0.26	0.75	0.84	0.01	0.32	0.01

[1] A total of 2,290 pigs (PIC 1050 × 337; initially 71.2 kg) were used in 2 replicated experiments with 26 to 28 gilts per pen and 10 to 13 pens per treatment.

[2] *P*-value of effect of SID Trp:Lys ratio dosage within each source of Trp.

[3] Phases were from d 0 to 20, 20 to 40, and 40 to 56 in Exp. 1 and from d 0 to 21, 21 to 47, and 47 to 68 in Exp. 2.

[4] Calculated % SID Trp in diet was used in the calculation of gram of SID Trp intake per kg of BW gain.

[5] Backfat, loin depth, and lean percentage were adjusted to a common HCW.

[6] Income over feed cost was calculated by subtracting the feed cost per pig from the gross income per pig. Gross income per pig is the income from selling one pig that was calculated from the total weight gain multiplied with carcass yield and carcass price. The average 5-year (2008 to 2012) price of corn, soybean meal, DDGS, and carcass weight reported by USDA was utilized. Corn was valued at $195/tonne, soybean meal at $384/tonne, DDGS at $178/tonne, L-Lys HCl at $1,762/tonne, DL-Met at $3,304/tonne, Thr at $2,533/tonne, L-Trp at $26,432/tonne, Ractopamine HCl at $70/kg, Phytase at $4.2/kg, and carcass price at $1.66/kg carcass weight.

Table 4.15 Main effects of increasing SID Trp:Lys ratio in dried distillers grains with solubles on growth performance and carcass characteristics of finishing pigs[1]

	SID Trp:Lys ratio, %					Probability, $P <$ SID Trp:Lys ratio	
	16	18	20	22	SEM	Linear	Quad
Replications	13	24	26	22			
Initial BW, kg	71.2	71.2	71.2	71.2	1.82	0.98	0.97
Final BW, kg	124.9	126.4	128.4	126.2	3.61	0.16	0.03
Phase 1[2]							
ADG, g	876	896	923	898	13.0	0.17	0.10
ADFI, g	2582	2524	2611	2514	39.4	0.41	0.50
G:F	0.340	0.356	0.354	0.357	0.007	0.04	0.22
Phase 2							
ADG, g	851	854	905	869	25.4	0.06	0.09
ADFI, g	2861	2859	3018	2982	78.2	0.01	0.58
G:F	0.297	0.300	0.300	0.292	0.004	0.36	0.16
Phase 3							
ADG, g	997	1053	1094	1023	25.1	0.31	0.01
ADFI, g	3167	3076	3144	3087	83.4	0.44	0.71
G:F	0.315	0.343	0.348	0.332	0.014	0.05	0.01

Overall							
ADG, g	897	921	958	918	9.17	0.02	0.01
ADFI, g	2834	2783	2891	2830	26.9	0.44	0.84
G:F	0.317	0.331	0.332	0.324	0.002	0.06	0.01
SID Trp g/kg gain[3]	3.8	4.1	4.6	5.1	0.04	0.01	0.01
Carcass wt, kg	93.2	94.8	95.6	93.7	3.76	0.50	0.01
Carcass yield, %	74.3	75.6	74.7	75.2	0.57	0.15	0.16
Backfat[4], mm.	14.8	14.5	14.4	14.5	1.02	0.19	0.30
Loin depth, mm.	71.9	70.0	70.7	70.7	0.40	0.13	0.02
Lean, %	58.5	58.4	58.6	58.5	0.62	0.63	0.97
IOFC[5], $/pig	21.3	24.2	23.8	21.8	4.02	0.62	0.01

[1] A total of 2,290 pigs (PIC 1050 × 337; initially 71.2 kg) were used in 2 replicated experiments with 26 to 28 gilts per pen. There were 13 pens per control treatment and 22 to 26 pens for main effect of 18 to 22 SID Trp:Lys ratio.

[2] Phases were from d 0 to 20, 20 to 40, and 40 to 56 in Exp. 1 and from d 0 to 21, 21 to 47, and 47 to 68 in Exp. 2.

[3] Calculated % SID Trp in diet was used in the calculation of gram of SID Trp intake per kg of BW gain.

[4] Backfat, loin depth, and lean percentage were adjusted to a common HCW.

[5] Income over feed cost was calculated by subtracting the feed cost per pig from the gross income per pig. Gross income per pig is the income from selling one pig that was calculated from the total weight gain multiplied with carcass yield and carcass price. The average 5-year (2008 to 2012) price of corn, soybean meal, DDGS, and carcass weight reported by USDA was utilized. Corn was valued at $195/tonne, soybean meal at $384/tonne, DDGS at $178/tonne, L-Lys HCl at $1,762/tonne, DL-Met at $3,304/tonne, Thr at $2,533/tonne, L-Trp at $26,432/tonne, Ractopamine HCl at $70/kg, Phytase at $4.2/kg, and carcass price at $1.66/kg carcass weight.

Table 4.16 Main effects of Trp sources in dried distillers grains with solubles on growth performance and carcass characteristics of finishing pigs[1]

	Trp source			
	Crystalline L-Trp	Soybean meal	SEM	Probability, *P* <
Replications	37	35		
Initial BW, kg	71.2	71.2	1.78	0.95
Final BW, kg	126.4	127.5	3.57	0.23
Phase 1[2]				
ADG, g	903	909	10.3	0.67
ADFI, g	2555	2544	35.5	0.73
G:F	0.354	0.358	0.007	0.43
Phase 2				
ADG, g	863	889	24.5	0.04
ADFI, g	2935	2971	76.1	0.26
G:F	0.295	0.299	0.003	0.23
Phase 3				
ADG, g	1052	1061	21.1	0.74
ADFI, g	3044	3161	79.2	0.02
G:F	0.346	0.336	0.013	0.11
Overall				
ADG, g	924	941	7.8	0.07
ADFI, g	2814	2856	22.5	0.13
G:F	0.329	0.330	0.002	0.75
SID Trp g/kg gain[3]	4.6	4.6	0.03	0.83
Carcass wt, kg	94.3	95.1	3.74	0.30
Carcass yield, %	75.3	75.0	0.55	0.23
Backfat[4], mm.	14.7	14.3	1.01	0.04
Loin depth mm.	70.2	70.7	0.31	0.23
Lean, %	58.3	58.6	0.62	0.02
IOFC[5], $/pig	23.0	23.5	4.03	0.42

[1]A total of 2,290 pigs (PIC 1050 × 337; initially 71.2 kg) were used in 2 replicated experiments with 26 to 28 gilts per pen with 35 to 37 pens per main effect of Trp source.

[2] Phases were from d 0 to 20, 20 to 40, and 40 to 56 in Exp. 1 and from d 0 to 21, 21 to 47, and 47 to 68 in Exp. 2.

[3] Calculated % SID Trp in diet was used in the calculation of gram of SID Trp intake per kg of BW gain.

[4] Backfat, loin depth, and lean percentage were adjusted to a common HCW.

[5] Income over feed cost was calculated by subtracting the feed cost per pig from the gross income per pig. Gross income per pig is the income from selling one pig that was calculated from the total weight gain multiplied with carcass yield and carcass price. The average 5-year (2008 to 2012) price of corn, soybean meal, DDGS, and carcass weight reported by USDA was utilized. Corn was valued at $195/tonne, soybean meal at $384/tonne, DDGS at $178/tonne, L-Lys HCl at $1,762/tonne, DL-Met at $3,304/tonne, Thr at $2,533/tonne, L-Trp at $26,432/tonne, Ractopamine HCl at $70/kg, Phytase at $4.2/kg, and carcass price at $1.66/kg carcass weight.

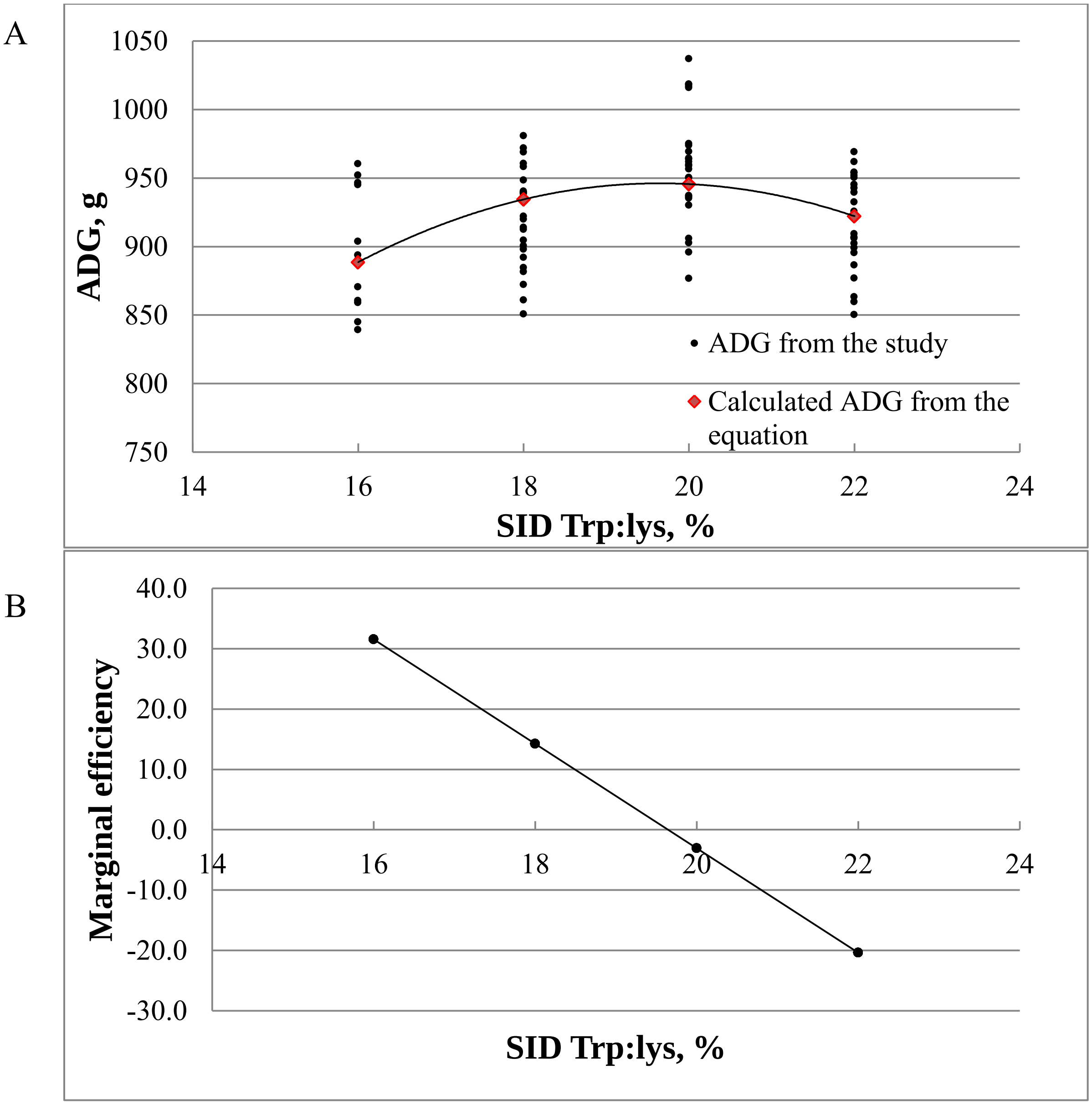

Figure 4.1 Relationship between ADG and SID Trp:Lys and the marginal efficiency

A) The quadratic relationship between ADG and SID Trp:Lys in the study generated from regression analysis [ADG = (- 4.3289 × % SID Trp:Lys2) + (170.09 × % SID Trp:Lys) – 724.64]. Points represent ADG response of each experimental unit (pen). B) The first derivative of the equation was used to describe an incremental response in ADG to an incremental unit of SID Trp:Lys or the marginal efficiency. The marginal efficiency curve illustrated a diminishing of return in ADG as SID Trp:Lys increased.

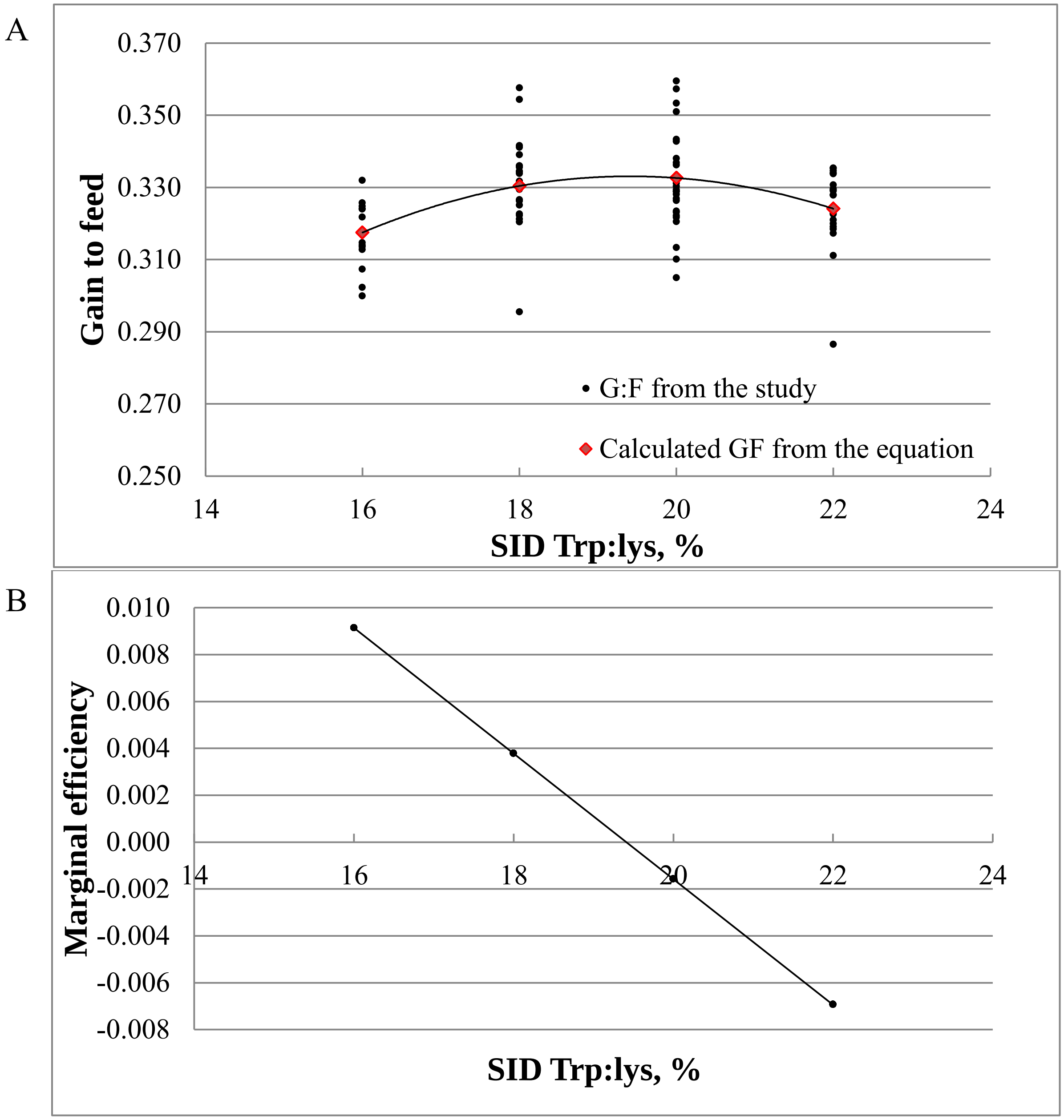

Figure 4.2 Relationship between G:F and SID Trp:Lys and the marginal efficiency

A) The quadratic relationship between G:F and SID Trp:Lys in the study generated from regression analysis [G:F = (-0.00134 × % SID Trp:Lys^2) + (0.05202 × % SID Trp:Lys) – 0.1718]. Points represent ADG response of each experimental unit (pen). B) The first derivative of the equation was used to describe an incremental response in G:F to an incremental unit of SID Trp:Lys or the marginal efficiency. The marginal efficiency curve illustrated a diminishing of return in G:F as SID Trp:Lys increased.

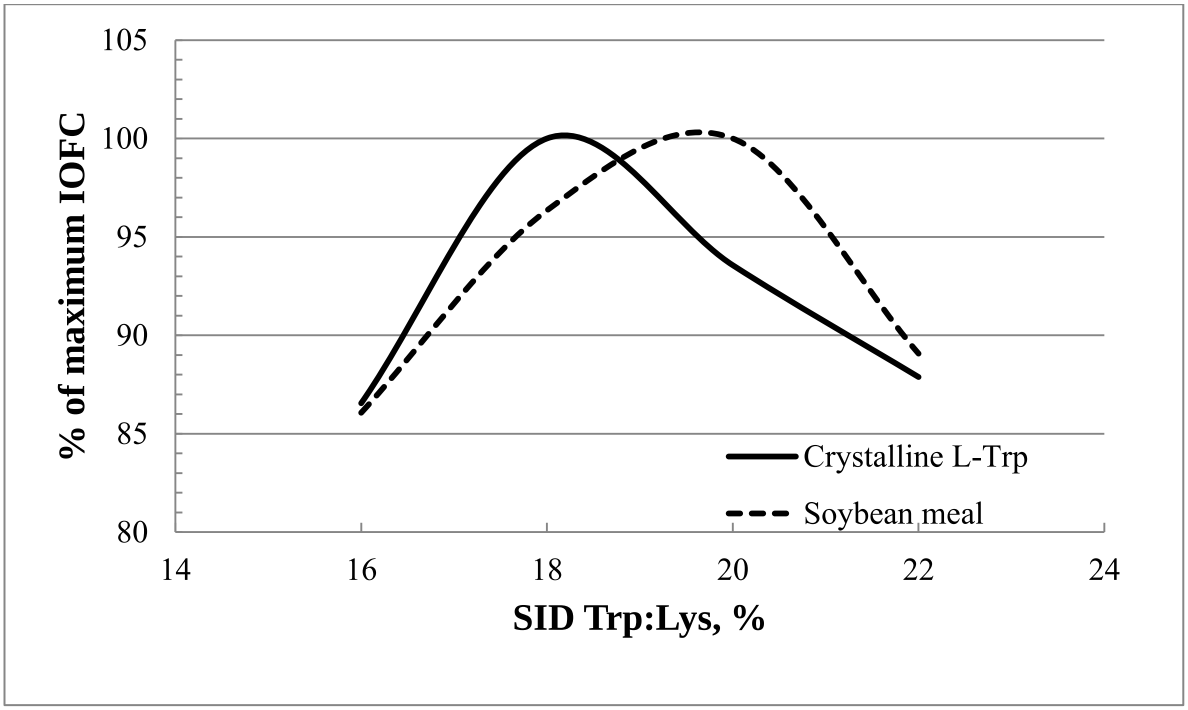

Figure 4.3 Income over feed cost of feeding SID Trp:Lys ratio

Income over feed cost (IOFC) evaluated by assuming that other costs, such as utility and labor, are equal and the only variables are ADG, carcass yield, feed usage, and feed cost. The best IOFC was observed at 20% SID Trp:Lys ratio with soybean meal as a source of Trp but at 18% with using crystalline L-Trp.

Chapter 5 - Determining the Effect of the Ratio of Tryptophan to Large Neutral Amino Acids on the Growth Performance of Finishing pigs

ABSTRACT

Large neutral amino acids (LNAA) share a common transport system with Trp resulting in a competitive absorption. Recent research indicates that the Trp requirement may be higher in finishing pig diets containing high levels of corn distillers dried grains with solubles (DDGS). Because LNAA are greatly increased in high DDGS diets, 96 pigs (PIC TR4 × 1050) were used in two 14-d studies to determine the effect of standardized ileal digestible (SID) Trp:LNAA ratio on growth performance. Experimental diets were fed in early- (35- to 48-kg BW) and late-finishing (83- to 99-kg BW) with a common diet between periods. Dietary treatments in early finishing included: (1) a corn-soybean meal-based diet without DDGS (3.8:1 Trp:LNAA), (2) a corn-soybean meal diet with 45% DDGS (3.0:1 Trp:LNAA), (3) a corn-soybean meal diet without DDGS but supplemented with similar amounts of LNAA as the diet containing 45% DDGS (3.0:1 Trp:LNAA), and (4) the LNAA-supplemented diet (treatment 3) with added crystalline L-Trp to increase the SID Trp:LNAA ratio (3.8:1). Diets in late finishing followed a similar format, but contained 30% DDGS and Trp:LNAA ratios of 4.1, 3.1, 3.1, and 4.1, respectively. Diets were formulated to 0.94 and 0.72% SID Lys in early and late finishing phase, respectively. Pens were allotted in a randomized complete block design with 4 pigs per pen (equal numbers of barrows and gilts) and 6 replications per treatment. From 35 to 48 kg, pigs fed

45% DDGS diet had poorer G:F (*P* = 0.01) compared with pigs fed other diets; however, no differences were found in other response criteria. From 83 to 99 kg, growth performance was not affected by dietary treatment. These results suggest that 16.5% SID Trp:Lys ratio was adequate to prevent a negative impact on growth when SID Trp:LNAA ratio was as low as 3.0% in finishing period.

Key words: Growth, large neutral amino acids, pig, tryptophan

INTRODUCTION

It is well documented that the large neutral amino acids (LNAA) which includes branched-chain amino acids (Ile, Leu, and Val) and aromatic amino acids (Phe and Tyr) share a common transport system with Trp resulting in a competitive absorption at the intestine and blood-brain barrier (Henry and Seve, 1993).The nutrients reported in NRC (2012) showed that the amount of Trp as a ratio to LNAA in dried distillers grains with solubles (DDGS) (1.6 to 2.3%) is lower than in corn (2.5%), soybean meal (5.7%), wheat (5.7 to 6.0%), or barley (5.5%). Thus, the high concentration of LNAA found in diets with DDGS might be responsible for any reduced growth performance and may also increase the Trp requirement to offset the competitive inhibition by LNAA for cell membrane transporters.

Thus, our objective in this study was to compare a corn-soybean meal diet to diets with 30 or 45% DDGS, and to a diet with similar LNAA ratios supplemented with and without Trp. In addition, a second objective was to evaluate if the high concentration of LNAA provided by

DDGS reduces growth performance and if adding addtitional Trp would mitigate the negative effect on growth performance.

MATERIALS AND METHODS

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment.

This experiment was conducted at the K-State Swine Teaching and Research Center in Manhattan, KS. The facility was a totally enclosed, environmentally regulated, mechanically ventilated barn containing 38 pens (2.4 × 3.1 m). The pens had adjustable gates facing the alleyway that allowed for $0.93 m^2$/pig. Each pen was equipped with a cup waterer and a single-sided, dry self-feeder (Farmweld, Teutopolis, IL) with 2 eating spaces located in the fence line. Pens were located over a completely slatted concrete floor with a 1.2-m pit underneath for manure storage. The facility was also equipped with a computerized feeding system (FeedPro; Feedlogic Corp., Willmar, MN) that delivered and recorded diets as specified. The equipment provided pigs with ad libitum access to food and water.

A total of 96 pigs (PIC TR4 × 1050) with an initial BW of 35 ± 1.4 kg were used in 2 14-d studies. A similar number of barrows and gilts were placed in each pen with 4 pigs per pen and 6 pens per treatment. Pens of pigs were allotted at the start of the early finishing phase and re-allotted before the late finishing phase to 1 of 4 dietary treatments in a completely randomized design while balancing for BW. The treatment diets were fed in 2 phases, early finishing phase (35- to 48-kg BW) and late finishing phase (83- to 98.5-kg BW), with a common diet fed between the 2 phases. Treatments included (1) a corn soybean-meal-based diet without DDGS (4.1:1 Trp:LNAA), (2) a corn-soybean meal-based diet with 45% DDGS (3.1:1 Trp:LNAA), (3) a corn-soybean meal-based diet without DDGS but supplemented with similar amounts of LNAA as the diet containing 45% DDGS (3.1:1 Trp:LNAA), and (4) the LNAA supplemented diet with added crystalline L-Trp to increase the SID Trp:LNAA ratio (4.1:1;Tables 5.1 and 5.2). The 45% DDGS diet was supplemented with L-Lys HCl to provide a minimum SID Trp:Lys ratio of 16.5%. Crystalline Ile, Val, Leu, Phe, and Tyr were added to provide the LNAA. Treatment diets contained 16.5% SID Trp:Lys ratio except the last diet, to which crystalline L-Trp was added to achieve a ratio of 21.0%. The diets were formulated in a similar manner for the late finishing phase with the exception that the DDGS level was lowered to 30% because only 30% inclusion was needed to achieve similar SID Trp:LNAA ratios used in early finishing diets (Tables 5.3 and 5.4). The SID Trp:LNAA ratios were 3.1 and 4.1% in early finishing phase and 3.0 and 3.8% in late finishing phase. The DDGS used in the 2 phases were not from the same lot but came from the same source. Nutrients and SID AA digestibility values used for diet formulation were obtained from NRC (1998) except for SID AA digestibility of DDGS were from Stein (2007). Diet samples were collected from feeders during every phase and stored at -20ºC, then amino acid analysis was conducted on composite samples by Ajinomoto Heartland LLC (Chicago, IL). Pens of pigs were weighed and feed disappearance was recorded at d 7 and 14 in each phase to determine ADG, ADFI, and G:F.

Statistical Analysis

The experimental data were analyzed using the MIXED procedure of SAS (SAS institute, Inc., Cary, NC). Pen was the experimental unit for all data analysis and significance and tendencies were set at $P \leq 0.05$ and $P \leq 0.10$, respectively.

RESULTS AND DISCUSSION

The analyzed AA contents were within the coefficient of variation between laboratories as reported by Cromwell et al. (1999) and AAFCO (2013) (Tables 5.5).

In the early finishing period (35- to 48-kg BW), pigs fed the 45% DDGS diet had poorer G:F ($P = 0.01$; Table 5.6) compared with pigs fed the other dietary treatments, which was a result of numerically lower ($P = 0.11$) ADG without a change in feed intake. No other differences occurred in other response criteria. During the late finishing period (83- to 98.5-kg BW), pig growth performance was not different among treatments (Table 5.7).

The competitive absorption between Trp and LNAA has been documented and proposed to be responsible for the lower utilization of Trp which results in a depressive feed intake and the subsequent growth performances (Le Floc'h and Seve, 2007; Zhang et al., 2007; Keszthelyi et al., 2009). Henry and associates (Henry et al., 1992; Henry and Seve, 1993; Henry et al., 1996) conducted series of experiments investigating the effect of elevating dietary LNAA in adequate and suboptimal-Trp diets in finishing pigs. They found a great reduction in feed intake and the subsequent growth rate and gain to feed in suboptimal-Trp diet but did not find a significant difference when diets were supplemented with Trp. Similar results were also reported by Peisker et al. (1998) when lowering the Trp:LNAA ratio from 5.8 to 2.3% did not affect nursery growth performance when diets were supplemented with Trp (0.26%); however, low Trp:LNAA ratio negatively impacted feed intake, growth rate, and feed efficiency in the low-Trp (0.21%) diets. From these studies, the excess LNAA appeared to decrease growth performance when the diet was low in Trp but the negative effects can be mitigated if the Trp was sufficiently supplied. Therefore, the similar performance when feeding corn-soybean meal and corn-soybean meal with LNAA diets observed in our study suggest that 16.5% SID Trp:Lys is adequate to prevent a negative impact on growth when SID Trp:LNAA was low (3.0%). This ratio is in agreement with the findings by Salyer et al. (2013) and Hinson et al. (2010) that found 16.5 to 16.0% SID Trp:Lys ratio to be optimal for less than 70-kg pigs fed high level of LNAA from an inclusion of 30% DDGS. Nevertheless, other studies (Nitikanchana et al., 2013; Salyer et al., 2013) on the Trp requirement in 70- to 130-kg BW pigs fed 30% DDGS found a higher SID Trp:Lys requirement of 20%. In the current study, increasing SID Trp:Lys ratio from 16.5 to 21% did not significantly impact growth performance of late-finishing pigs; however, there was a numeric improvement in ADG (4.6%), ADFI (1.7%), and G:F (3.2%) from adding Trp to corn-soybean meal diet with LNAA. The magnitudes of improvement we observed were close to the results of those requirement studies where ADG, ADFI, and G:F were improved by 6 to7%, 2 to 4%, and 3 to 4% when SID Trp:Lys ratio increased from 16 or 16.5 to 20% in 70- to 130-kg BW pigs fed 30% DDGS diets (Nitikanchana et al., 2013; Salyer et al., 2013). A longer period of Trp supplement in those studies (52 to 73 d) may explain the discrepancy as our study was conducted in a short period (14 d) due to the high cost of crystalline LNAA.

The SID Lys level is very imperative to accurately determine the Trp requirement as a ratio to Lys. The Lys level that is over the requirement can underestimate the optimal Trp to Lys ratio as excess Lys is not used for protein accretion (Susenbeth and Lucanus, 2005). In this study, the SID Lys was formulated at slightly lower than the recommended levels by NRC (2012) at similar BW range; therefore, the underestimation of the SID Trp:Lys was not suspected to be responsible for the lack of response to increasing SID Trp:Lys ratio.

Feeding 30% DDGS to late-finishing pigs resulted in a similar performances compared with feeding corn-soybean meal diet; however, pigs fed the 45% DDGS diet had poorer feed efficiency from a numeric decreased growth rate while feed intake was similar to other diets in early-finishing period. The similar feed intake suggested that Trp was adequate in DDGS diets as the reduction in feed intake which is the hallmark of Trp deficiency would have been observed (Burgoon et al., 1992; Eder et al., 2003; Salyer et al., 2013). Therefore, other factors may contribute to the decreased growth rate and feed efficiency in early-finishing period. One explanation is the excess of other essential and non-essential amino acids which increases energy cost from its catabolism, resulting in adverse feed efficiency which is a common effect when feeding excess protein (Noblet et al., 1987; Henry and Seve, 1993).

Another important consideration is the use of crystalline LNAA to decrease SID Trp:LNAA in our study. The free amino acids generally pass through and are absorbed in the gastrointestinal tract more rapidly than the intact amino acids (Wang and Fuller, 1989). Therefore; the LNAA may increase in plasma before intact protein amino acid, including Trp, resulting in a less competitive transport through the blood brain barrier. This may partly contribute to the lack of difference between low and high SID Trp:LNAA in our study.

In conclusion, the results of the study suggest that 16.5% SID Trp:Lys is adequate to prevent a negative impact on growth when SID Trp:LNAA as low as 3.0% was fed in finishing period. More research is needed to determine the effect of LNAA on Trp requirement in diets containing high level of DDGS.

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FIGURES AND TABLES

Table 5.1 Composition of diets (early finishing phase, 35- to 48-kg BW; as-fed basis)[1]

SID Trp:LNAA[2], %:	4.1	3.1	3.1	4.1
SID Trp:Lys, %:	16.5	16.5	16.5	21.7
Ingredient, %				
Corn	76.06	40.81	76.06	76.06
Soybean meal (46.5% CP)	19.94	11.78	19.94	19.94
DDGS[3]	---	45.00	---	---
Corn starch	1.28	---	0.05	---
Monocalcium P (21% P)	0.65	---	0.65	0.65
Limestone	0.95	1.35	0.95	0.95
Salt	0.35	0.35	0.35	0.35
Trace mineral premix[4]	0.15	0.15	0.15	0.15
Vitamin premix[5]	0.15	0.15	0.15	0.15
Lys HCl	0.31	0.41	0.31	0.31
DL-Met	0.05	---	0.05	0.05
L-Thr	0.11	---	0.11	0.11
L-Trp	---	---	---	0.05
L-Ile	---	---	0.10	0.10
L-Val	---	---	0.18	0.18
L-Leu	---	---	0.61	0.61
L-Phe	---	---	0.19	0.19
L-Tyr	---	---	0.15	0.15
TOTAL	100	100	100	100

[1] Treatment diets were fed for 14 d from 35- to 48-kg BW.

[2] Amount of Trp in the diet as a ratio to large neutral amino acids (LNAA; Ile, Leu, Val, Phe, and Tyr) on standadized ileal digestible (SID) basis.

[3] Dried distillers grains with solubles.

[4] Provided per kg of premix: 4,409,200 IU vitamin A; 551,150 IU vitamin D3; 17,637 IU vitamin E; 1,764 mg vitamin K; 3,307 mg riboflavin; 11,023 mg pantothenic acid; 19,841 mg niacin; and 15.4 mg vitamin B12.

[5] Provided per kg of premix: 26.5 g Mn from manganese oxide, 110 g Fe from iron sulfate, 110 g Zn from zinc sulphate, 11 g Cu from copper sulfate, 198 mg I from calcium iodate, and 198 mg Se from sodium selenite.

Table 5.2 Nutrient compositions (early finishing phase, 35- to 48-kg BW; as-fed basis)[1]

SID Trp:LNAA[2], %:	4.1	3.1	3.1	4.1
SID Trp:Lys, %:	16.5	16.5	16.5	21.7
Calculated analysis				
SID amino acid, %				
Lys	0.94	0.94	0.94	0.94
Ile:Lys	60	71	71	71
Leu:Lys	143	207	207	207
Met:Lys	31	36	31	31
Met & Cys:Lys	57	73	57	57
Thr:Lys	65	66	65	65
Trp:Lys	16.5	16.5	16.5	21.7
Val:Lys	70	88	88	88
Phe:Lys	74	94	94	94
Tyr:Lys	53	69	69	69
His:Lys	41	50	41	41
Trp:BCAA[3]	6.0	4.5	4.5	5.9
Total LNAA, %	4.5	3.4	3.4	4.4
Total Trp:LNAA, %	3.9	5.8	5.1	5.1
Total Lys, %	1.04	1.13	1.04	1.04
ME, kcal/kg	3,344	3,348	3,311	3,311
SID Lys:ME, g/Mcal	2.81	2.81	2.84	2.84
CP, %	16.1	21.6	16.4	16.4
Ca, %	0.57	0.58	0.57	0.57
P, %	0.49	0.52	0.49	0.49
Available P, %	0.29	0.38	0.29	0.29

[1] Treatment diets were fed for 14 d from 35- to 48-kg BW.

[2] Amount of Trp in the diet as a ratio to large neutral amino acids (LNAA; Ile, Leu, Val, Phe, and Tyr) on standadized ileal digestible (SID) basis.

[3] Amount of Trp in the diet as a ratio to branched-chain amino acids (BCAA; Ile, Leu, Val) on SID basis.

Table 5.3 Composition of diets (late finishing phase, 83- to 98.5-kg BW; as-fed basis)[1]

SID Trp:LNAA[2], %:	3.8	3.0	3.0	3.8
SID Trp:Lys, %:	16.5	16.5	16.5	21.0
Ingredient, %				
Corn	83.32	60.30	83.32	83.32
Soybean meal (46.5% CP)	13.19	7.59	13.19	13.19
DDGS[3]	---	30.00	---	---
Corn starch	0.84	---	0.03	---
Monocalcium P (21% P)	0.65	---	0.65	0.65
Limestone	0.95	1.15	0.95	0.95
Salt	0.35	0.35	0.35	0.35
Trace mineral premix[4]	0.15	0.15	0.15	0.15
Vitamin premix[5]	0.15	0.15	0.15	0.15
Lys HCl	0.25	0.31	0.25	0.25
DL-Met	0.05	---	0.05	0.05
L-Thr	0.11	---	0.11	0.11
L-Trp	---	---	---	0.03
L-Ile	---	---	0.06	0.06
L-Val	---	---	0.11	0.11
L-Leu	---	---	0.41	0.41
L-Phe	---	---	0.13	0.13
L-Tyr	---	---	0.11	0.11
TOTAL	100	100	100	100

[1] Treatment diets were fed for 14 d from 83- to 98.5-kg BW.

[2] Amount of Trp in the diet as a ratio to large neutral amino acids (LNAA; Ile, Leu, Val, Phe, and Tyr) on standadized ileal digestible (SID) basis.

[3] Dried distillers grains with solubles.

[4] Provided per kg of premix: 4,409,200 IU vitamin A; 551,150 IU vitamin D3; 17,637 IU vitamin E; 1,764 mg vitamin K; 3,307 mg riboflavin; 11,023 mg pantothenic acid; 19,841 mg niacin; and 15.4 mg vitamin B12.

[5] Provided per kg of premix: 26.5 g Mn from manganese oxide, 110 g Fe from iron sulfate, 110 g Zn from zinc sulphate, 11 g Cu from copper sulfate, 198 mg I from calcium iodate, and 198 mg Se from sodium selenite.

Table 5.4 Nutrient compositions (late finishing phase, 83- to 98.5-kg BW; as-fed basis)[1]

SID Trp:LNAA[2], %:	3.8	3.0	3.0	3.8
SID Trp:Lys, %:	16.5	16.5	16.5	21.0
Calculated analysis				
SID amino acid, %				
Lys	0.72	0.72	0.72	0.72
Ile:Lys	63	72	72	72
Leu:Lys	165	221	221	221
Met:Lys	36	38	36	36
Met & Cys:Lys	66	78	66	66
Thr:Lys	72	68	72	72
Trp:Lys	16.5	16.5	16.5	21.0
Val:Lys	76	91	91	91
Phe:Lys	80	97	97	97
Tyr:Lys	56	70	70	70
His:Lys	44	52	44	44
Trp:BCAA[3]	5.4	4.3	4.3	5.5
Total LNAA, %	3.3	4.6	4.1	4.1
Total Trp:LNAA, %	4.1	3.2	3.3	4.1
Total Lys, %	0.81	0.87	0.81	0.81
ME, kcal/kg	3,344	3,355	3,319	3,322
SID Lys:ME, g/Mcal	2.15	2.14	2.17	2.17
CP, %	13.6	17.1	13.7	13.7
Ca, %	0.55	0.49	0.55	0.55
P, %	0.46	0.43	0.46	0.46
Available P, %	0.29	0.30	0.29	0.29

[1] Treatment diets were fed for 14 d from 83- to 98.5-kg BW.
[2] Amount of Trp in the diet as a ratio to large neutral amino acids (LNAA; Ile, Leu, Val, Phe, and Tyr) on standadized ileal digestible (SID) basis.
[3] Amount of Trp in the diet as a ratio to branched-chain amino acids (BCAA; Ile, Leu, Val) on SID basis.

Table 5.5 Total amino acid (AA) analysis of diets (as-fed basis)[1]

SID Trp:LNAA[2], %:	4.1	3.1	3.1	4.1
SID Trp:Lys, %:	16.5	16.5	16.5	21.7
Early finishing phase, 35- to 48-kg BW				
Total AA, %				
Lys	1.05 (1.04)	1.22 (1.13)	0.95 (1.04)	0.99 (1.04)
Met	0.30 (0.31)	0.37 (0.40)	0.29 (0.31)	0.29 (0.31)
Cys	0.27 (0.29)	0.37 (0.42)	0.26 (0.29)	0.26 (0.29)
Thr	0.68 (0.70)	0.76 (0.81)	0.66 (0.70)	0.66 (0.70)
Trp	0.19 (0.18)	0.23 (0.20)	0.19 (0.18)	0.21(0.22)
Ile	0.63 (0.64)	0.78 (0.82)	0.69 (0.74)	0.69 (0.74)
Leu	1.33 (1.18)	1.97 (2.09)	1.77 (1.79)	1.80 (1.79)
Val	0.74 (0.75)	0.95 (1.03)	0.86 (0.92)	0.87 (0.92)
Phe	0.77 (0.77)	0.98 (1.05)	0.88 (0.96)	0.85 (0.96)
Tyr	0.40 (0.55)	0.58 (0.77)	0.46 (0.70)	0.50 (0.70)
Total LNAA	4.5 (3.9)	6.0 (5.8)	5.4 (5.1)	5.4 (5.1)
Total Trp:LNAA, %	4.3 (4.5)	3.7 (3.4)	3.5 (3.4)	4.0 (4.4)
Late finishing phase, 83- to 98.5-kg BW				
Total AA, %				
Lys	0.74 (0.81)	0.87 (0.87)	0.75 (0.81)	0.77 (0.81)
Met	0.23 (0.28)	0.29 (0.32)	0.24 (0.28)	0.23 (0.28)
Cys	0.21 (0.26)	0.30 (0.34)	0.21 (0.26)	0.21 (0.26)
Thr	0.55 (0.59)	0.61 (0.63)	0.56 (0.59)	0.55 (0.59)
Trp	0.15 (0.14)	0.13 (0.15)	0.14 (0.14)	0.17 (0.17)
Ile	0.48 (0.52)	0.61(0.64)	0.54 (0.58)	0.55 (0.58)
Leu	1.15 (1.11)	1.66 (1.71)	1.51(1.51)	1.50 (1.51)
Val	0.58 (0.62)	0.77 (0.81)	0.68 (0.73)	0.68 (0.73)
Phe	0.61 (0.64)	0.79 (0.82)	0.73 (0.76)	0.73 (0.76)
Tyr	0.27 (0.45)	0.46 (0.59)	0.34 (0.55)	0.35 (0.55)
Total LNAA	3.6 (3.3)	4.9 (4.6)	4.3 (4.1)	4.4 (4.1)
Total Trp:LNAA, %	4.2 (4.1)	2.7 (3.2)	3.2 (3.3)	3.8 (4.1)

[1]Diet samples were collected from feeders and stored at -20ºC, then total amino acid analysis was conducted on composite samples by Ajinomoto Heartland LLC, Chicago, IL.
[2]Amount of Trp in the diet as a ratio to large neutral amino acids (LNAA; Ile, Leu, Val, Phe, and Tyr) on standadized ileal digestible (SID) basis.

Table 5.6 Effect of Trp to large neutral amino acid (LNAA) ratio on the growth performance of early finishing pigs (35- to 48-kg BW)[1]

Treatments[2]	Corn-SBM	45 % DDGS	Corn-SBM +LNAA	Corn-SBM +LNAA+Trp	SEM	Probability, *P* <
SID Trp:LNAA[3], %	4.1	3.1	3.1	4.1		
SID Trp:Lys, %	16.5	16.5	16.5	21.7		
Pig BW, kg						
d 0	35.1	35.1	35.2	35.2	1.38	1.00
d 14	48.8	47.1	48.7	48.5	1.76	0.90
d 0 to 14						
ADG, g	982	859	961	949	35.5	0.11
ADFI, g	2,135	2,113	2,062	2,106	79.0	0.93
G:F	0.460[a]	0.409[b]	0.466[a]	0.451[a]	0.011	0.01

[1] A total of 96 pigs (PIC TR4 × 1050, initially 35 kg) were used in 2 14-d studies with 4 pigs per pen and 6 pens per treatment. Treatment diets were fed from 35- to 48-kg BW in early finishing period.

[2] Treatments included (1) a corn-soybean meal-based diet without dried distillers grains with solubles (DDGS), (2) a corn soybean-meal-based diet with 45% DDGS, (3) a corn-soybean meal-based diet without DDGS but supplemented with similar amounts of LNAA as a diet containing 45% DDGS, and (4) the LNAA-supplemented diet with added crystalline Trp to increase the standadized ileal digestible (SID) Trp:LNAA ratio.

[3] Amount of trp in the diet as a ratio to large neutral amino acids (LNAA; Ile, Leu, Val, Phe, and Tyr) on SID basis.

Table 5.7 Effect of Trp to large neutral amino acid (LNAA) ratio on the growth performance of late finishing pigs (83- to 98.5-kg BW)[1]

Treatments[2]	Corn-SBM	30 % DDGS	Corn-SBM +LNAA	Corn-SBM +LNAA+Trp	SEM	Probability, *P* <
SID Trp:LNAA[3], %	3.8	3.0	3.0	3.8		
SID Trp:Lys, %	16.5	16.5	16.5	21.0		
Pig BW, kg						
d 0	82.9	83.1	83.0	82.9	2.35	1.00
d 14	98.0	98.0	98.8	99.4	2.46	0.97
d 0 to 14						
ADG, g	1,074	1,066	1,128	1,182	64.3	0.56
ADFI, g	3,115	2,992	3,116	3,169	91.4	0.58
G:F	0.343	0.355	0.361	0.373	0.012	0.43

[1] A total of 96 pigs (PIC TR4 × 1050, initially 35 kg) were used in 2 14-d studies with 4 pigs per pen and 6 pens per treatment Treatment diets were fed from 83- to 98.5 kg-BW in late finishing period.

[2] Treatments included (1) a corn-soybean meal-based diet without dried distillers grains with solubles (DDGS), (2) a corn soybean-meal-based diet with 30% DDGS, (3) a corn-soybean meal-based diet without DDGS but supplemented with similar amounts of LNAA as a diet containing 45% DDGS, and (4) the LNAA-supplemented diet with added crystalline Trp to increas the standadized ileal digestible (SID) Trp:LNAA ratio.

[3] Amount of Trp in the diet as a ratio to large neutral amino acids (LNAA; Ile, Leu, Val, Phe, and Tyr) on SID basis.

Chapter 6 - Regression Analysis to Predict Growth Performance from Dietary Net Energy in Growing-Finishing Pigs

ABSTRACT

Energy concentration in livestock feed is often altered to optimize pig growth performance and feed cost. Therefore, an accurate prediction of growth performance as affected by feeding different energy concentrations is crucial to determine the optimal dietary energy concentration. Data from 41 trials with multiple energy levels, extracted from 17 journal articles, 10 technical memos, and a thesis resulting in 285 observations was used in a meta-analysis. Nutrient and energy levels in all diets were estimated using the NRC (2012) ingredient library. A mixed model using experiment within trial as a random effect was used to develop a regression equations to predict ADG or G:F. Predictor variables examined for best fit models using AIC criteria included linear and quadratic terms of NE, average BW, CP, standardized ileal digestible (SID) Lys, crude fiber, NDF, ADF, fat, and ash, including their interaction terms. The initial best fit models included interactions between NE and CP or SID Lys. After removal of the observations that fed SID Lys below the suggested requirement, these terms were no longer significant. Resulting best fit prediction equation for ADG was ADG (g) = [0.1135 × NE (kcal/kg)] + [8.8142 × Average BW (kg)] – [0.05068 × Average BW (kg) × Average BW (kg)] + 276. Including dietary fat in the model with NE and average BW significantly improved G:F prediction model resulting in the best fit equation for G:F; G:F = [0.000096 × NE (kcal/kg)] – [0.0025 × Average BW (kg)] + [0.003071 × Fat (%)] + 0.3257. The meta-analysis indicated that, as long as diets are adequate for other nutrients (i.e., Lys), dietary NE is adequate to predict

changes in ADG across a wide variety of trials with different dietary ingredients and under different environmental conditions. The analysis indicates that ADG increases by 11 g/d for every 100 kcal/kg increase in dietary NE. Also, ADG increases with heavier average BW, but decreases when average BW is above 87 kg. For feed efficiency, G:F improves with increasing dietary NE and fat, and decreases with increasing BW. Including dietary fat improves the fit of the equation indicating that NE may underestimate the influence of fat on feed efficiency.

Key words: Growth performance, growing-finishing pig, net energy, regression

INTRODUCTION

Dietary energy components represent the greatest portion of the feed cost and over half the total cost in swine production. Increased energy concentration in diets has been shown to improve growth performance but simultaneously increase feed costs (De La Llata et al., 2007). Given the increased price of traditional dietary energy sources, the swine industry has shifted to using more high-fiber, low-energy diets in order to reduce feed costs. However, feeding lower energy diets decreases growth performance. Therefore, in order to evaluate the tradeoff between lower growth performance and lower diet costs the prediction of growth performance is essential to quantify the effect of dietary energy.

Digestible (DE) and metabolizable energy (ME) are the most commonly used energy systems in swine industry; however, these energy values do not account for the varying metabolic utilization and production of heat increments between nutrients. The energy value of feed with a high content of fiber or protein is overestimated, whereas the energy of fat or starch is underestimated (Noblet, 2007). For this reason, net energy (NE) should be the most accurate system to evaluate the effect of dietary energy on growth performance, but NE is difficult to measure, and few estimates of NE are available for many by-product ingredients. Therefore, the purpose of this study was to obtain regression equations to predict growth rate and feed efficiency of growing-finishing pigs based on dietary NE content using meta-analysis.

MATERIALS AND METHODS

A literature search was conducted via Kansas State University Libraries using the internet and the CABI search engine using the keywords “energy and growth and pig” or “fiber and growth and pig”. Data was also derived from both refereed and non-refereed publications including theses, technical memos, and university publications. The search was restricted to dates from 1991 through November 2012. All publications were initially screened by determining that the research was conducted on growing-finishing pigs (> 20 kg BW) and provided growth performance responses. Screening left 36 publications providing 50 trials.

Selection for inclusion and exclusion criteria

For inclusion, treatment diets in the trials had to vary in dietary DE, ME, or NE. Other criteria included: pigs used in the trial had to have ad libitum access to feed and water, treatments had to be replicated (> 4 replications /treatment), and the experimental design had to include randomization (completely randomized design [CRD], or randomized complete block design, [RCBD]). The number of pigs per pen was also investigated and the single trial that used only one pig per pen was excluded. The diet ingredients and their inclusion rates used in each dietary treatment had to be clearly stated such that diets could be re-created. All diets were then reformulated using the NRC ingredient library (chapter 17, NRC 2012) as a reference for nutrients. The treatment that used SID Lys below 65% of the requirement based on the equations adapted from Main et al. (2008) [Gilts SID Lys:NE ratio : – 0.000000153 × ((Initial BW (kg) + Final BW (kg)) × 1.1)^3 + 0.000104928 × ((Initial BW (kg) + Final BW (kg)) × 1.1)^2 - 0.030414451 × ((Initial BW (kg) + Final BW (kg)) × 1.1) + 6.043540689; Barrow SID Lys:NE ratio : 0.0000454 × ((Initial BW (kg) + Final BW (kg)) × 1.1)^2 – 0.0249885 × ((Initial BW (kg) + Final BW (kg)) × 1.1) + 5.8980083] in the trial was excluded. Also, the trials had to have ingredients that were listed in NRC (2012) ingredient library. Trials using intact males, immunocastrated males, or fed Ractopamine HCl were not considered. After excluding trials using these criteria, 41 trials were extracted from 17 journal articles, 10 technical memos, and a thesis.

Data from each selected trial was then recorded in a template; the template included the mean ADG and G:F for each treatment in each feeding period. If the report did not provide responses in each period, the overall mean was recorded. Average BW of each treatment was also extracted by averaging the initial and final BW of each period. Days on feed of each period were included in the template and used to calculate final BW of pigs fed each treatment from ADG and initial BW when the report omitted the periodic BW range. Other information included during the data extraction process was number of pig per pen, replications, gender, genetic background, type of study (CRD or RCBD), dietary treatment, basic diet information (corn, soybean meal, wheat, barley, oat, wheat middlings, wheat bran), and type of report (journal article, technical memo, thesis).

Diet composition calculations

Dietary treatment of each trial was reformulated using a spreadsheet-based software program to obtain dietary nutrient content. Dietary nutrient content was derived from accumulating the nutrient of each ingredient according to its proportion in the diet. The NRC ingredient library (chapter 17, NRC, 2012) was used as a reference for nutrient ingredients in diet reformulation. The dietary NE (kcal/kg), CP (%), standardized ileal digestible (SID) Lys (%), crude fiber (CF, %), NDF (%), ADF (%), fat (%), and ash (%) on an as-fed basis were obtained and recorded in the template for each dietary treatment.

Preparation of database

All of the selected trials reported the overall growth performance, and some also reported growth performance by period. For those trials that reported growth performance by period, growth performance and nutrient profile by period were recorded in database as different experiments. In trials that reported overall performance but listed the feed formulation by period, the average dietary NE and nutrient content pooled across periods was used to correspond with the overall growth performance.

To avoid the effects of factors other than energy, trials that had a factorial design were divided into experiments by factors that were crossed with the energy factor. Factors divided into separate experiments were CP, fat source, with or without wheat middlings, and yellow dent vs. NutriDense corn.

Overall, data from 100 experiments in 41 trials were used as a database for the statistical analysis (Table 6.1). Pigs used in the database could be described as modern genetic lines with BW from 21 to 138 kg BW, with the trial average BW ranging from 33.2 to 127.8 kg. Most of the trials (20) applied treatments to barrows and gilts in a single-sex pen; however, due to the lack of interaction with gender, these trials reported the main effect averaged across gender. Some trials were conducted using mixed-sex pens (5), and some used only barrows (4) or gilts (12); thus, data used in the analysis were derived from both single-sex and mixed-sex pens.

Statistical analysis

The PROC MIXED procedure of SAS (SAS institute, Inc., Cary, NC) was used to develop a regression equation to predict ADG or G:F depending on BW and NE content. The method of maximum likelihood (ML) was used in the model selection. The dietary NE applied within each experiment (285 observations) was the experimental unit for the modeling of the equation, and experiment within trial was included as a random effect. Linear and quadratic terms of NE, average BW, CP, SID Lys, CF, NDF, ADF, fat, and ash, including their interaction term, were the variables in the regression analysis. The statistical significance for inclusion of terms in the models was determined at $P < 0.10$. Further evaluation of models with significant terms was then conducted based on the Akaike Information Criteria (AIC), where models that minimized AIC were preferred candidate models. Minimizing AIC has been shown to result in regression models that have better precision (Littell et al., 2002). The method of residual maximum likelihood (REML) was then used to obtain the estimate of the parameters for the candidate models. The adequacies of candidate models were also examined using residual analysis. Briefly, this consisted of evaluating a histogram of residuals for evidence of normality and plotting studentized residuals against the corresponding fitted values (Kuehl, 2000). Subsequently, a second regression model was developed by eliminating all observations that were fed SID Lys below the requirement based on the same equation used in the inclusion criteria.

RESULTS AND DISCUSSION

The database included diets with a range of 1,980 to 2,815 kcal/kg NE, 8.9 to 22.9 % CP, 0.51 to 1.15% SID Lys, 1.9 to 12.5% CF, 6.7 to 29.5% NDF, 2.5 to 14.9% ADF, 3.1 to 6.7% ash, and 1.8 to 10% fat.

Prediction equations for ADG

The equation predicting ADG using dietary NE as a single predictor (AIC = 3,019) was improved when including the average BW in the model (AIC = 3,018). Because of the improvement in the precision of the model and because growing-finishing swine feed is generally formulated according to BW range, average BW was included in the model. The regression analysis showed that the model with dietary NE, average BW, CP, SID Lys, and the interaction between dietary NE and CP (NE × CP) demonstrated the smallest AIC (AIC = 3,001; Table 6.2) compared with other significant models. Having the interaction between NE and SID Lys (NE × SID Lys) in the model with dietary NE, average BW, and SID Lys resulted in a slightly greater AIC (3,002). The interaction between NE and CP or SID Lys indicated that the magnitude of improvement in ADG by dietary NE was maximized when CP or SID Lys level increased (Figure 6.1). Generally, feed intake is adjusted according to energy density in the diet to achieve a suitable amount of energy intake on a daily basis; thus, feeding a high-energy diet results in a reduction in feed intake, which in turn can compromise the amount of amino acids consumed per day (Campbell and Taverner, 1986; Tokach et al., 1992). Limiting amino acids intake therefore restricts the growth response to dietary energy. On the contrary, when formulating a diet at low energy density, feed intake increases and amino acids can be consumed to meet the requirement. Therefore, increasing amino acids density in low-energy diet has smaller influence on growth compared with increases in a high-energy dense diet.

The interaction between dietary NE and CP or SID Lys suggests that SID Lys concentrations were limiting growth rate across many of the trials included in the analysis. Therefore, the observations that fed SID Lys below the suggested requirement were then removed from the database, resulting in 104 observations from 17 trials incorporating a range of 1,980 to 2,746 kcal/kg NE, 12.3 to 22.9 % CP, 0.61 to 1.15% SID Lys, 2.2 to 12.5% CF, 6.8 to 29.5% NDF, 3.1 to 14.9% ADF, 3.7 to 6.7% ash, 1.8 to 9% fat, and 36.2 to 127.8 kg average BW for re-analysis. This eliminated SID Lys or CP as a significant predictor. Instead, the simple model with dietary NE, average BW, and the quadratic term of average BW demonstrated the smallest AIC (1,071) compared with other significant models (Table 6.3). The model indicated that increasing dietary NE resulted in a linear improvement in ADG. Also, ADG increases with heavier average BW, but decreases when average BW is above 87 kg (Figure 6.2).

Prediction equations for G:F

The AIC values of all significant equations to predict G:F were negative; however, the same principal can be applied to compare the precision of equations (Burnham and Anderson, 1998). Thus, the equation that minimized the AIC value; in this case, the equation with the most negative AIC value was preferred. The equation to predict G:F using dietary NE as a single predictor resulted in an AIC value of –1,320. Including the interaction between dietary NE and Lys (NE × SID Lys) with dietary NE, average BW, and SID Lys in the model significantly improved AIC (–1,470) which was the smallest AIC compared with other significant models. Therefore, the equation to predict G:F from dietary NE obtained from this regression method was a function of dietary NE, average BW, SID Lys, and NE × SID Lys (Table 6.2). The equation showed that feed efficiency improved with the increase in dietary NE. However, similar to the ADG model, the magnitude of improvement in feed efficiency by dietary NE was maximized when SID Lys level increased which suggested that SID Lys levels were limiting growth across many of the trials in database (Figure 6.3).

When trials that fed SID Lys below the suggested requirement were removed from the database, the equation to predict G:F that presented the best AIC (–601) was a function of dietary NE, average BW, and fat, which showed that G:F improved with increasing dietary NE, fat, and lower BW (Table 6.3; Figure 6.4). The improvement of G:F with fat in the model may suggest that the NE value of fat is underestimated. With the right estimation of diet ingredients, dietary NE should be the only nutrient that influences feed efficiency.

Application of prediction equations

Discrepancies in health status, genetics, and environment between farms could make a difference between the predicted value and the actual growth rate or feed efficiency. One method to adjust for these factors is to assume the shape and magnitude of the response is similar across these factors and adjusts the intercept of the presented equations to provide farm specific estimates. The first step would be to assess if the SID Lys:NE ratio fed is above or below the suggested requirement. With this method, a set of data on NE and SID Lys of diet that was fed to a certain BW on the farm can be used to calculate the ADG and G:F from the predicting equation. The difference between predicted and actual value of growth performance is then used to adjust the intercept of the equation; for instance, the 90- to 110-kg pigs in farm A demonstrated a growth rate and feed efficiency of 915 g/day and 0.312 when feeding a corn-soybean meal diet that contained 2,511 kcal/kg NE and 3% fat. Based on these feed characteristics and BW range, the predicting equation would calculate the growth rate of 936 g/day (ADG = $(0.1135 \times 2511) + (8.8142 \times 100) - (0.05068 \times 100 \times 100) + 275.99$) and G:F of 0.317 (G:F = $(0.000096 \times 2511) - (0.0025 \times 100) + (0.003071 \times 3) + 0.3257$). As a result, the actual ADG was 21 g/day lower than the predicted value; thus, the intercept of the ADG prediction equation can be adjusted to 255 (275.99 – 21). Likewise, the 0.005 G:F difference between predicted and actual value was used to adjust the intercept of G:F prediction equation to 0.3207 (0.3257 – 0.005). Subsequently, the adjusted equations can then be used to model different economic scenarios based on dietary NE concentrations provided by different ingredients.

These prediction equations were developed from a certain database thus should be used to predict growth performance within the range of nutrients in the database. Therefore, caution should be used if using the predictions for ingredients and nutrients outside the range used in the database. In addition, the experiments pertained in our database were conducted with ad-libitum feeding. In other circumstances where feed intake is restricted, the magnitude of improvement in growth rate and feed efficiency by changing dietary NE may be different than predicted in the model as the compensation of energy intake by adjusting feed consumption is limited.

In conclusion, dietary NE is an important predictor of the growth performance of growing-finishing pigs. Our regression analysis showed that improvements in growth rate and feed efficiency could be obtained by increasing dietary NE across a wide variety of trials with different dietary ingredients and under different environmental conditions. However, the magnitude of improvement in growth performances by dietary NE will be minimized if the dietary amino acids or other nutrients are limiting. Regression equations from this paper can be used to predict the influence of dietary NE on ADG and G:F; however, these equations still need validation from growth studies not included in their development.

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FIGURES AND TABLES

Table 6.1 Summary of papers used in the regression analysis to predict growth performance from dietary net energy in growing-finishing pigs

First author, year	Source type: J = journal T = thesis M = technical memo	Trials	Gender[1]	Range of dietary NE, (kcal/kg)	Range of CP, (%)	Initial BW, (kg)	Final BW, (kg)	Diet
Friesen et al., 1991[2]	J	1	both	2560-2784	16.8-17.2	57.9	89.9	Sorghum-SBM
Myer and Comb, 1991	J	1	both	2204-2619	14.3-14.9	27.0	102.0	Corn-SBM-Oat
Lopez-Bote et al., 1997	J	1	both	2257-2409	17.5-17.7	30.4-30.5	89.1-90.1	Barley-SBM-sunflower meal
Smith et al., 1997	M	1	gilt	2515-2626	10.7-17.6	47.7	106.9-115.5	Corn-SBM
Knowles et al., 1998	J	3	gilt, barrow	2499-2733	8.9-15.6	63.0-83.0	101.0-119.2	Corn-SBM-wheat middlings-rice bran
Smith et al., 1999[3]	J	2	gilt	2402-2726	16.4-21.9	29.2-44.5	104.3-107	Corn-SBM
De la Llata et al., 2001[4]	J	1	both	2396-2786	13.9-22.9	36.0	118.0-121.6	Corn-SBM
Engel et al., 2001	J	1	gilt	2523-2775	13.7-14.4	59.2-61.0	109.8-111.7	Corn-SBM
Baudon et al., 2003	M	1	both	2469-2809	14.0-17.3	57.7	127.3	Corn-SBM
Kerr et al., 2003[5]	J	1	gilt	2393-2534	11.3-21.4	25.3	109.7	Corn-SBM-wheat middlings
Shriver et al., 2003[5]	J	1	both	2529-2688	12.2-15.7	28.4-28.8	114-117.5	Corn-SBM-Soybean hull
Young et al., 2003	M	1	both	2500-2746	16.3-17.2	71.8	105.5	Corn-SBM
Hastad et al., 2005[5]	J	1	gilt	2434-2815	14.9-20.9	50.1	113.9-117.0	Corn-SBM

Hastad et al., 2005	M	2	gilt	2442-2735	16.9-20.7	30.6-35.3	117.5-120.0	Corn-SBM
Benz et al., 2007	M	1	both	2500-2785	15.5-17.0	54.5	133.9	Corn-Sorghum-SBM
De la Llata et al., 2007[3]	J	2	gilt, barrow	2405-2749	15.1-22.6	24.0-34.0	120.0	Corn-SBM
Duttlinger et al., 2008	M	1	both	2534-2788	14.2-14.7	77.9	102.6	Corn-SBM
Apple et al., 2009	J	1	mixed	2484-2797	11.5-17.0	28.1	113.6	Corn-SBM
Beaulieu et al., 2009	J	2	both	2187-2572	14.7-20.4	31.06-37.4	115.0-119.0	Wheat-Barley-SBM-canola meal
Ball et al., 2010	J	1	both	2215-2304	20.9-21.3	39.7-39.8	90.9-93.4	Wheat-Barley-SBM
Asmus et al., 2011[6]	M	1	both	2343-2546	13.4-20.9	40.9-41.0	120.5-122.6	Corn-SBM-DDGS-wheat middlings
Barns et al., 2011	T	1	both	2408-2491	16.8-17.3	46.6	129.8-134.9	Corn-SBM-DDGS-wheat middlings
Barns et al., 2011	T	1	both	2423-2710	16.0-17.0	42.3	128.2-136.9	Corn-SBM-DDGS Wheat middlings
Barns et al., 2011[7]	T	1	both	2409-2619	15.1-18.6	48.1	121.0-124.8	Corn-SBM-DDGS Wheat middlings
Benz et al., 2011	J	1	both	2495-2732	15.5-16.1	44.1	123.0	Corn-SBM
Chen et al., 2011	J	2	barrow	2329-2701	12.2-16.5	62.0-69.0	95.0-98.0	Corn-SBM-wheat bran
Chu et al., 2012	J	3	mixed	2260-2650	13.6-20.9	20.8-78.6	55.9-105.8	Corn-SBM-wheat bran
Graham et al., 2012[8]	M	1	mixed	2359-2537	13.9-20.0	53.0	121.9	Corn-SBM-DDGS-Wheat middlings

Jungst et al., 2012	M	3	both	2368-2709	15.4-20.3	28.6-30.4	135.2-138.2	Corn-SBM-DDGS-Wheat middlings
Jungst et al., 2012	M	1	gilt	1980-2480	12.3-19.5	33.9-34.3	118.9-121.2	Corn-SBM-soyhulls-Wheat middlings

[1] "Both" in gender category refers to applying treatments to barrows and gilts in a single-sex pen; "mixed" refers to trials that applied treatments in mixed-sex pen.

[2] Only data for diets supplemented with 0.2% Lys were used in the analysis.

[3] Only data for diet with Lys:calorie ratio at the requirement as indicated in the literature were used in the analysis.

[4] Two experiments were reported in the literature, but only data from experiment 1 were used in the analysis.

[5] Two experiments were reported in the literature, but only data from experiment 2 were used in the analysis.

[6] Data from treatments that fed low-NDF and high-NDF diets throughout the experiment without withdrawal periods were used in the analysis.

[7] Only data from feeding diets without xylanase were used.

[8] Data of treatments that fed corn-SBM without ractopamine and diets with 30% DDGS and 19% midds without ractopamine throughout the experiment without withdrawal periods were used in the analysis.

Table 6.2 Regression equations to predict ADG and G:F from dietary NE using ingredient NE values from NRC (2012)[1]

Growth performance	Model	AIC[2]
ADG (g)	= – 0.1809 × NE (kcal/kg) + 1.6119 × Average BW (kg) – 34.2735 × CP (%) + 0.01476 × NE (kcal/kg) × CP (%) + 129.63 × SID Lys (%) + 1047.92	3,001
	= – 0.1004 × NE (kcal/kg) + 1.6744 × Average BW (kg) – 289.56 × SID Lys (%) + 0.1918 × NE (kcal/kg) × SID Lys (%) + 836.56	3,002
	= 0.09988 × NE (kcal/kg) + 0.7571 × Average BW (kg) + 557.62	3,018
G:F	= 0.000004365 × NE (kcal/kg) – 0.00162 × Average BW (kg) – 0.08023 × SID Lys (%) + 0.000094 × NE (kcal/kg) × SID Lys (%) + 0.3496	–1,470
	= 0.000118 × NE (kcal/kg) – 0.00233 × Average BW (kg) + 0.2455	–1,416

[1] Data from 41 trials divided into 100 experiments were used as a database for the statistical analysis.

[2] Akaike Information Criteria (AIC) were used to compare the precision of the model where the model with smaller AIC value was preferred. The AIC values of all significant equations to predict G:F were negative; however, the same principal can be applied to compare the precision of equations. Thus, the equation that minimized AIC value; in this case, the equation with the most negative AIC value was preferred.

Table 6.3 Regression equation to predict ADG and G:F from dietary NE using ingredient NE values from NRC (2012) after removing observations feeding SID Lys below the suggested requirement[1]

Growth performance	Model	AIC[2]
ADG (g)	= 0.1135 × NE (kcal/kg) + 8.8142 × Average BW (kg) – 0.05068 × Average BW (kg) × Average BW (kg) + 275.99	1,071
G:F	= 0.000096 × NE (kcal/kg) – 0.0025 × Average BW (kg) + 0.003071 × Fat (%) + 0.3257	–601

[1] Trials that fed SID Lys below the requirement were removed from the database, resulting in 104 observations from 17 trials for regression analysis.

[2] Akaike Information Criteria (AIC) were used to compare the precision of the model where the model with smaller AIC value was preferred. The AIC values of all significant equations to predict G:F were negative; however, the same principal can be applied to compare the precision of equations. Thus, the equation that minimized AIC value; in this case, the equation with the most negative AIC value was preferred.

Figure 6.1 Predicted ADG of 76-kg pig fed increasing dietary NE (kcal/kg) at varying levels of SID Lys (%)

The predicted ADG was calculated using the model [ADG (g/day) = – 0.1004 × NE (kcal/kg) + 1.6744 × Average BW (kg) – 289.56 × SID Lys (%) + 0.1918 × NE (kcal/kg) × SID Lys (%) + 836.56] (SID = standardized ileal digestible). Increasing dietary NE resulted in a linear improvement in ADG; however, the rate of improvement (slope) was different due to the level of SID Lys. The magnitude of improvement in ADG by increasing dietary NE was maximized when SID Lys level increased.

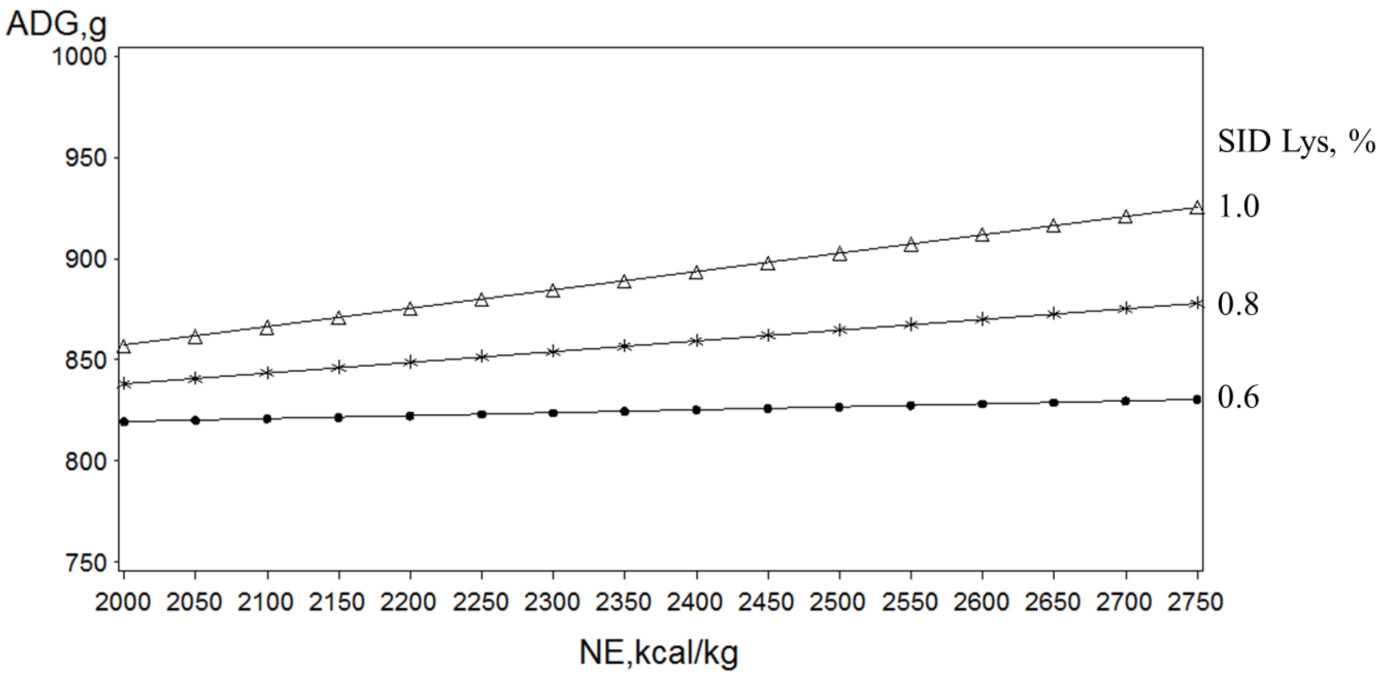


Figure 6.2 Predicted ADG of pigs fed varying levels of dietary NE

The predicted ADG was calculated using the model [ADG (g/day) = 0.1135 × NE (kcal/kg) + 8.8142 × Average BW (kg) – 0.05068 × Average BW (kg) × Average BW (kg) + 275.99]. Growth rate increases with heavier average BW, but decreases when average BW is above 87 kg.

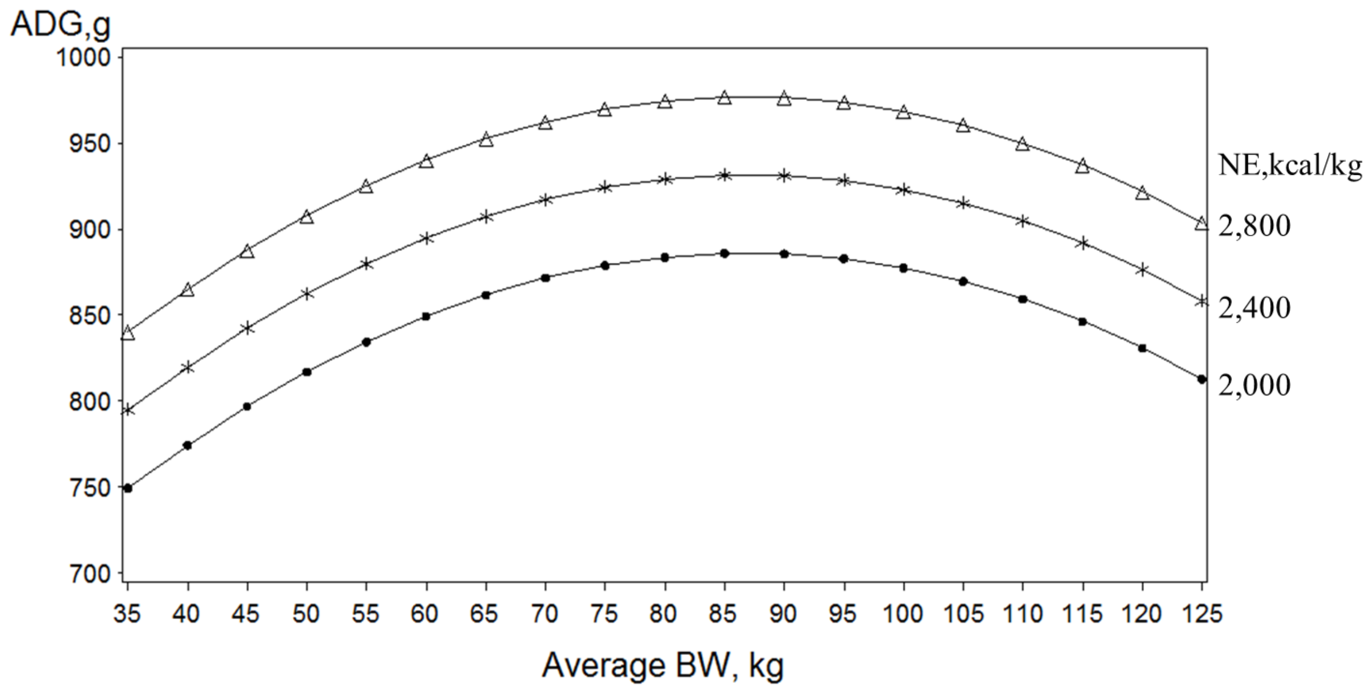


Figure 6.3 Predicted G:F of 76-kg pig fed increasing dietary NE (kcal/kg) at varying levels of SID Lys (%)

The predicted G:F was calculated using the model [G:F = 0.000004365 × NE (kcal/kg) – 0.00162 × Average BW (kg) – 0.08023 × SID Lys (%) + 0.000094 × NE (kcal/kg) × SID Lys (%) + 0.3496] (SID = standardized ileal digestible). Increasing dietary NE resulted in a linear improvement in G:F; however, the rate of improvement (slope) was different due to the level of SID Lys. The magnitude of improvement in G:F by increasing dietary NE was maximized when SID Lys level increased.

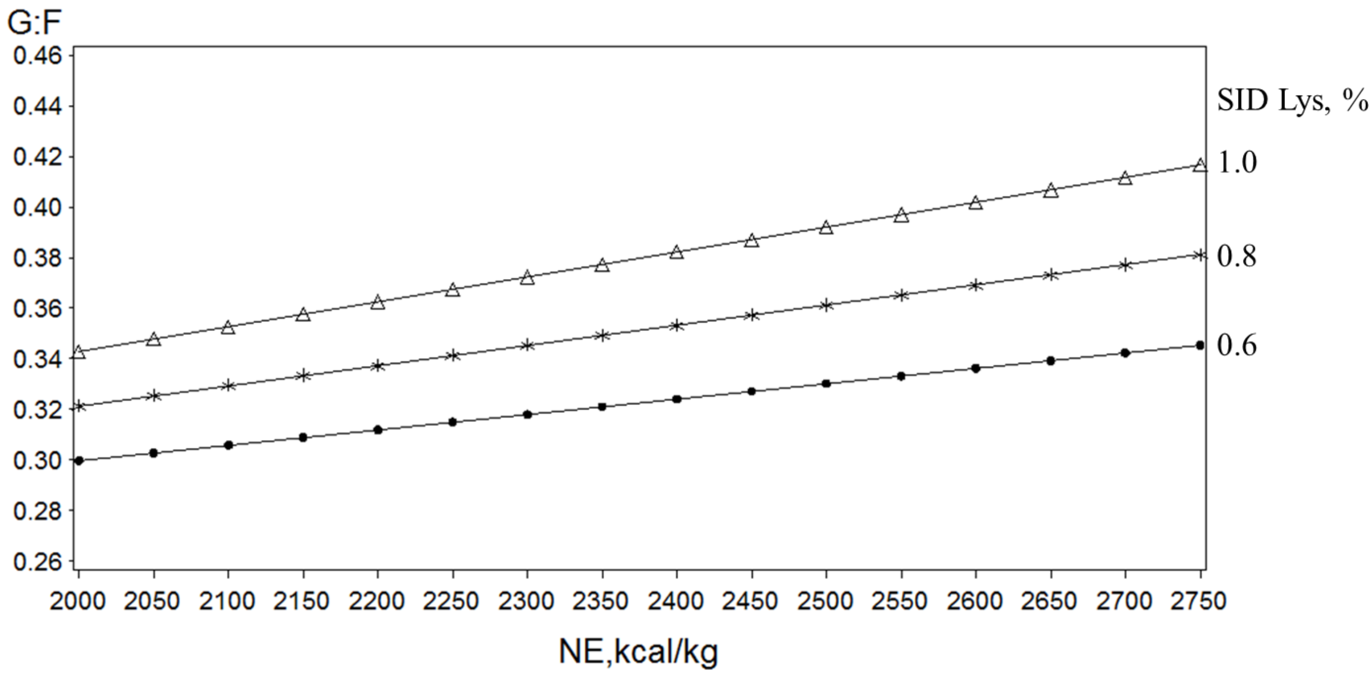
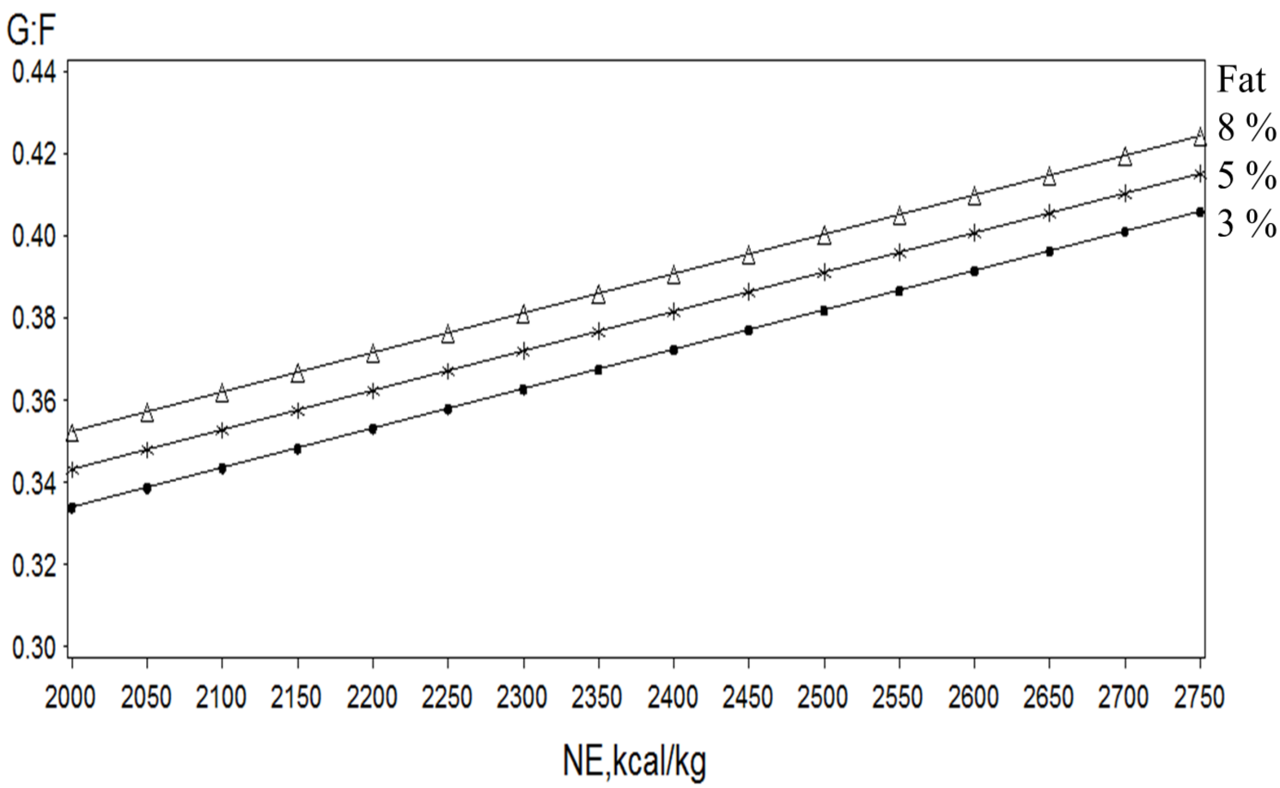


Figure 6.4 Predicted G:F of 76-kg pig fed increasing dietary NE (kcal/kg) at varying levels of fat (%)

The predicted G:F was calculated using the model [G:F = 0.000096 × NE (kcal/kg) – 0.0025 × Average BW (kg) + 0.003071 × Fat (%) + 0.3257]. Gain to feed improved with increasing dietary NE, fat, and lower BW.



Chapter 7 - The Effect of Feeding Different Dietary Net Energy Levels to Growing-Finishing Pigs when Dietary Lysine is Adequate

ABSTRACT

A total of 543 pigs (PIC 1050 × 327: PIC Hendersonville, TN) were used in 2 consecutive experiments with initial BW of 48 and 57 kg in Exp. 1 and 2, respectively. The objective was to validate the regression equations predicting growth rate and feed efficiency of growing-finishing pigs based on dietary net energy (NE) content by comparing actual and predicted performance. Thus, the 5 treatments included diets with: (1) 30% dried distillers grains with solubles (DDGS), 20% wheat middlings, and 4 to 5% soybean hulls (low-energy), (2) 20% wheat middlings and 4 to 5% soybean hulls (low-energy), (3) a corn-soybean meal diet (medium-energy), (4) diet (2) supplemented with 3.7% choice white grease (CWG) to equalize NE level to diet (3) (medium-energy), and (5) a corn-soybean meal diet with 3.7% CWG (high-energy). In Exp. 1 and 2, increasing dietary NE increased (linear, $P < 0.01$) final weight, ADG, and G:F, but decreased ($P < 0.11$) ADFI. Only small differences were observed between predicted and observed value of ADG and G:F except for the low-energy diet containing highest fiber content (30% DDGS diet) where ADG and G:F were over-predicted by 3 to 6%. Carcass weight and carcass yield increased (linear, $P = 0.01$) with increasing dietary NE. Also, backfat depth increased (linear, $P = 0.01$), loin depth decreased (quadratic, $P = 0.05$), and lean percentage decreased (linear, $P = 0.01$) with increasing dietary NE. A decreased (linear, P = 0.01) jowl IV was also observed with increasing dietary NE. No differences ($P > 0.26$) in net

energy caloric efficiency (NEE) on live weight basis were observed with increasing dietary NE. Nevertheless, feeding 30% DDGS diet resulted in a poorer (*P* = 0.05) NEE on carcass basis compared with feeding other diets. In conclusion, the prediction equations provided a good estimation of growth rate and feed efficiency of growing-finishing pigs fed different levels of dietary NE except for the pigs fed low-energy diet containing highest fiber content. These predictions of growth performance can then be used to model economic value of different dietary energy strategies.

Key words: Growth, growing-finishing pig, net energy, regression

INTRODUCTION

Energy concentration in feed is often altered to optimize pig growth performance and feed cost. Increased energy concentration in diets has been shown to improve growth performance but simultaneously increase feed costs (De La Llata et al., 2007). Therefore, the swine industry has recently shifted to using more high-fiber, low-energy diets in order to reduce feed costs. However, feeding lower energy diets decreases growth performance. In order to evaluate the tradeoff between growth performance and diet costs, the prediction of growth performance is thus essential to quantify the effect of dietary energy. Recently, a meta-analysis was conducted to predict growth rate and feed efficiency of growing-finishing pigs based on dietary net energy (NE) content which revealed that improvements in growth rate and feed efficiency could be obtained by increasing dietary NE across a wide variety of trials with different dietary ingredients and under different environmental conditions. However, the magnitude of improvement in growth performance by increasing dietary NE will be minimized if the amino acids are limiting. Therefore, this study was conducted to validate these newly developed prediction equations by comparing actual and predicted performance of growing-finishing pigs fed different dietary NE levels where dietary Lys was provided above the requirement.

MATERIALS AND METHODS

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in these experiments. The experiments were conducted at the K-State Swine Teaching and Research Center in Manhattan, KS. The facility was a totally enclosed, environmentally regulated, mechanically ventilated barn containing 38 pens (2.4× 3.1m). The pens had adjustable gates facing the alleyway that allowed for 0.74 m^2/pig. Each pen was equipped with a cup waterer and a single-sided, dry self-feeder (Farmweld, Teutopolis, IL) with 2 eating spaces located in the fence line. Pens were located over a completely slatted concrete floor with a 1.2-m pit underneath for manure storage. The facility was also equipped with a computerized feeding system (FeedPro; Feedlogic Corp., Willmar, MN) that delivered and recorded diets as specified. The equipment provided pigs with ad libitum access to feed and water.

A total of 543 pigs (PIC 1050 × 327: PIC Hendersonville, TN) were used in 2 consecutive experiments with initial BW of 48 and 57 kg in Exp. 1 and 2, respectively. There were 4 barrows and 4 gilts per pen and 13 to 14 pens per treatment. Pens of pigs were assigned to 1 of 5 dietary treatments in a completely randomized design while balancing for initial BW within study. The dietary treatments included 3 different levels of dietary NE by adding low-energy ingredients (wheat middlings or soybean hulls), 30% dried distillers grains with solubles (DDGS), or choice white grease (CWG) to a corn-soybean meal-based diet. Thus, the 5 treatments included diets with: (1) 30% DDGS, 20% wheat middlings, and 4 to 5% soybean hulls (low-energy), (2) 20% wheat middlings and 4 to 5% soybean hulls (low-energy), (3) a corn-soybean meal diet (medium-energy), (4) diet (2) supplemented with 3.7% CWG to equalize NE level to diet (3) (medium-energy), and (5) a corn-soybean meal diet with 3.7% CWG (high-energy). The difference in dietary NE content between high vs. medium and medium vs. low energy was 166 kcal/kg across all phases of feeding. The NRC ingredient library (chapter 17, NRC, 2012) was used as a reference for nutrient ingredients in diet formulation except for DDGS. Samples of DDGS were analyzed for oil content (Ward labs, Kearney NE; Table 7.1) prior to feed manufacturing and used to determine the NE content from the equation: NE (kcal/kg) = 115.011×oil (%) + 1501.01 (Nitikanchana et al., 2013). The equation adapted from Main et al. (2008) [Gilts SID Lys:NE ratio : – 0.000000153 × ((Initial BW (kg) + Final BW (kg)) × 1.1)^3 + 0.000104928 × ((Initial BW (kg) + Final BW (kg)) × 1.1)^2 - 0.030414451 × ((Initial BW (kg) + Final BW (kg)) × 1.1) + 6.043540689; Barrow SID Lys:NE ratio : 0.0000454 × ((Initial BW (kg) + Final BW (kg)) × 1.1)^2 – 0.0249885 × ((Initial BW (kg) + Final BW (kg)) × 1.1) + 5.8980083] was used to calculate the SID Lys requirement at different dietary energy levels and BW. The SID Lys was formulated at 105% requirement of the lightest BW pig fed the highest energy level in each feeding phase to ensure that the SID Lys intake was above the requirement. All diets were fed in meal form and fed in 3 phases from 48 to 57, 57 to 76, and 76 to 98 kg in Exp. 1, and 57 to 77, 77 to 98, and 98 to 124 kg in Exp. 2 (Tables 7.2 through 7.7). Thus, Exp. 1 was terminated prior to harvest at a lighter BW than in Exp. 2. Diet samples were collected from feeders during every phase and stored at -20ºC, then the proximate analysis was conducted on composite samples (Ward labs, Kearney NE).

Pens of pigs were weighed and feed disappearance was recorded at d 9, 29, and 53 in Exp. 1 and at d 21, 44, and 74 in Exp. 2 to determine ADG, ADFI, and G:F. At the end of Exp. 2, pigs were individually weighed and transported to a commercial packing plant (Triumph Foods LLC, St. Joseph, MO) for processing and carcass data collection. Before slaughter, pigs were tattooed to allow for carcass data collection. Hot carcass weights (HCW) were measured immediately after evisceration, and carcass criteria of backfat depth and loin depth were collected using an optical probe. Carcass yield percentage was calculated by dividing carcass weight at the plant by live weight at the farm, and percentage lean was calculated by the processor using a proprietary equation that depended on backfat and loin depth. Net energy caloric efficiencies (NEE) were calculated on a pen basis by multiplying total feed intake by the dietary NE concentration and dividing by total live or carcass weight gain. The carcass weight gain was obtained from subtracting HCW from the initial carcass weight by assuming 75% carcass yield across all pigs.

Statistical analysis

The experimental data were analyzed using the MIXED procedure of SAS (SAS institute, Inc., Cary, NC) where treatment was a fixed effect. Pen was the experimental unit for all data analysis. Significance and tendencies were set at $P \leq 0.05$ and $P \leq 0.10$, respectively. Analysis of backfat depth, loin depth, and percentage lean were adjusted to a common HCW. Contrast coefficients were used to evaluate linear and quadratic responses to dietary NE level.

Calculations of predicted performance

Prediction equations used in the analysis were used to calculate predicted ADG and G:F by feeding phase [ADG (g/day) = 0.1135 × NE (kcal/kg) + 8.8142 × Average BW (kg) – 0.05068 × Average BW (kg) × Average BW (kg) + 275.99; G:F = 0.000096 × NE (kcal/kg) –

0.0025 × Average BW (kg) + 0.003071 × fat (%) + 0.3257]. The actual BW at the beginning and end of each phase was averaged and used to represent the average BW in the equation. The total gain in each phase was then calculated by multiplying the predicted ADG and days on feed for each phase. Next, the total gain for each phase was divided with the predicted G:F in that phase to calculate the total feed intake for each phase. Lastly, the overall G:F was obtained by dividing the summation of total gain with the summation of total feed intake, and the overall ADG was calculated by dividing the summation of total gain with the overall day on feed. To accommodate the variation between baseline predicted and actual performance, the difference between predicted and actual growth performance of pigs fed corn-soybean meal diet was used to adjust the intercept of the prediction equations thus adjusting the growth performance of the other pens fed the other diets.

RESULTS

The proximate analysis of diet samples was in agreement with the calculated values in the diet formulation for both Exp. 1 and 2 (Table 7.8 and 7.9).

Experiment 1

For the overall period (d 0 to 53), increasing dietary NE resulted in increased final BW, ADG, and G:F, but decreased ADFI (linear, $P < 0.04$; Table 7.10). Pigs fed the diet with wheat middlings and soybean hulls had greater ($P < 0.01$) ADG and G:F than those fed the diet containing 30% DDGS, wheat middlings, and soybean hulls; however, there was no difference ($P = 0.83$) in ADFI. Pigs fed the corn-soybean meal diet had similar ADG and ADFI ($P > 0.34$) but poorer feed efficiency ($P = 0.05$) compared with pig fed diets with wheat middlings, soybean hull, and CWG.

The prediction equations overestimated ADG and G:F of pigs fed the diet containing 30% DDGS, wheat middlings, and soybean hulls by 4.5 and 6.1 %, respectively. However, only small differences between predicted and actual ADG and G:F were observed when feeding other diets where the predicted growth performance was within the 95% confidence interval of the actual performance.

There was no difference in NEE on live weight basis due to increasing dietary NE ($P > 0.26$). Nevertheless, feeding the diet containing wheat middlings and soybean hulls resulted in similar ($P = 0.22$) NEE to pigs fed those diet with CWG, but resulted in an improved ($P < 0.01$) NEE compared with other diets. Pigs fed the wheat middlings and soybean hulls containing diet with CWG had similar ($P > 0.06$) NEE to those fed the corn-soybean meal diet with or without CWG, but had improved ($P = 0.03$) NEE than those fed the diet containing 30% DDGS, wheat middlings, and soybean hulls. No differences ($P > 0.16$) in NEE was observed between pigs fed 30% DDGS diet, corn-soybean meal diet, and corn-soybean meal diet with addition of CWG.

Experiment 2

For the overall period (d 0 to 74), increasing dietary NE increased (linear, $P < 0.01$; Table 7.11) final weight, ADG, and G:F, but tended ($P = 0.11$) to decrease ADFI. Pigs fed the diet containing wheat middlings and soybean hulls tended ($P = 0.08$) to have greater G:F than those fed the diet containing 30% DDGS, wheat middlings, and soybean hulls; however, there were no differences ($P > 0.41$) in ADG and ADFI. Pigs fed the diet with wheat middlings, soybean hulls, and CWG had similar ($P > 0.14$) ADG, ADFI, and G:F to those fed corn-soybean meal diet.

The prediction equations overestimated ADG and G:F of pigs fed the diet containing 30% DDGS, wheat middlings, and soybean hulls by 3.2 and 6.1 %, respectively. However, the predicted ADG and G:F of pigs fed with other diets were within the 95% confidence interval of the actual performance.

For carcass characteristics, carcass weight and carcass yield linearly increased (*P* = 0.01) with increasing dietary NE. In addition, backfat depth increased (linear, *P* = 0.01) and loin depth decreased (quadratic, *P* = 0.05) with increasing dietary NE resulting in a reduction of lean percentage (linear, *P* = 0.01). A decreased (linear, *P* = 0.01) jowl IV was also observed with increasing dietary NE. Pigs fed the diet containing 30% DDGS, wheat middlings, and soybean hulls tended to have lower carcass weight (*P* = 0.11), carcass yield (*P* = 0.01), and backfat depth (*P* = 0.06), but had greater lean percentage (*P* = 0.01) and jowl IV (*P* = 0.01) than pigs fed the diet containing wheat middlings and soybean hulls; however, there was no difference (*P* = 0.19) in loin depth. Pigs fed the wheat middling, soybean hulls, and CWG diet had lower (*P* = 0.02) carcass yield and greater (*P* = 0.01) jowl IV than those fed corn-soybean meal diet; however, there were no differences (*P* > 0.26) in carcass weight, backfat depth, loin depth, and lean percentage.

No differences (*P* = 0.35) in NEE on a live weight basis were observed with increasing dietary NE and across diets. Nevertheless, feeding the diet containing 30% DDGS, wheat middlings, and soybean hulls resulted in poorer (*P* = 0.05) NEE on carcass basis compared with feeding other diets.

DISCUSSION

An improvement in ADG and G:F with increasing dietary NE in Exp. 1 and 2 agreed with the prediction equations derived from the meta-analysis in chapter 6. These equations indicate a linear improvement in ADG and G:F when dietary NE increases. Lower feed intake was also observed with increasing dietary NE indicating an adjustment of feed intake according to energy density to achieve a suitable amount of energy intake on a daily basis (Campbell and Taverner, 1986).

From the prediction equations developed in Chapter 6 of this dissertation, feeding diets with the same dietary NE should result in similar ADG as long as the dietary SID Lys is adequate. This is based on the equations where as long as pigs were fed adequate Lys, dietary NE was the only significant dietary predictor for growth rate. As predicted in both experiments, pigs fed the corn-soybean meal diet with added CWG had the best growth rate. Adding CWG to a diet with wheat middlings and soybean hulls to restore the dietary NE to those of corn-soybean meal diet resulted in a similar growth rate to feeding corn-soybean meal diet as predicted. This result was similar in both Exp. 1 and 2. However, pigs fed the diet containing 30% DDGS, wheat middlings, and soybean hulls had lower ADG than those fed the diet with wheat middlings and soybean hulls that had the same dietary NE in both experiments. Average daily gain was 4.5 and 3.2% lower than predicted in Exp. 1 and Exp. 2, respectively. Whereas ADG of pigs fed the diet with wheat middlings and soybean hulls was similar to the predicted value in both experiments.

Dried distillers grains with solubles, wheat middlings, and soybean hulls are fibrous ingredients that when combined together resulted in higher fiber than other diets in the experiments. The bulkiness property of dietary fiber would increase mastication time and stimulate the mechanoreceptors in the gastrointestinal tract which will promote a meal termination, thus limiting the meal size (Leeuw et al., 2008). This limitation of intake by fiber could result in a lower amount of energy being consumed per day when increasing fiber content in diets and consequently limiting the growth response. Nevertheless, the feed intake of pigs fed the diet containing 30% DDGS, wheat middlings, and soybean hulls was not negatively affected compared with feeding the diet with only wheat middlings and soybean hulls even though the dietary fiber content was higher when DDGS was also included. Another effect of fiber to be considered is the increase in size and weight of gastro-intestinal tract (Turlington and Stahly, 1984). The proliferation of intestinal cells will result in a higher demand for energy to support the increase of protein turnover in the epithelial lining of the gut (Johnston et al., 2003). Thus, energy requirements for maintenance are increased and a lower amount of energy from the diet is used for growth. This would explain the poorer ADG in pigs fed the diet containing 30% DDGS, wheat middlings, and soybean hulls compared with those fed the diet with only wheat middlings and soybean hulls and may also explain the overestimation of the prediction equation. Another consideration would be that the NE of DDGS was overestimated. In this study, NE of DDGS was estimated to be 91 to 95% of NE of corn in diet formulation.

Adding CWG to the corn-soybean meal based diet improved ADG by 2.8% in Exp. 1 and was similar to the predicted improvement (2.1%). Nevertheless, in Exp. 2 adding CWG to corn-soybean meal diet resulted in a 4.3% increase in ADG. The finishing pig is known to have greater potential for lipid deposition than the growing pig and leads to the hypothesis that NE of fat is also greater in finishing period (Kil et al., 2011). Therefore, the greater ADG response to adding CWG in Exp. 2 might be due to the longer finishing period in this experiment compared with Exp. 1 that only conducted until 98 kg BW. However, the study by Kil et al. (2011) found no differences in NE of CWG between growing and finishing period. Therefore, the discrepancy might be simply due to the random variation between the experiments.

Little difference (0.25 to 2.2%) between observed and predicted G:F was noted for all treatments except for pigs fed the diet containing 30% DDGS, wheat middlings, and soybean hulls. For the pigs fed the diet containing 30% DDGS, wheat middlings, and soybean hulls, G:F was 6.1% lower than predicted in Exp. 1 and 2. The good agreement between determined and predicted G:F from the prediction equation that accounts for fat content suggests that the value of adding fat to the diet is underestimated by NE calculations.

In the prediction equation for G:F, both dietary NE and fat content were significant dietary predictors. Therefore, the equation predicted greater G:F for the wheat middlings and soybean hulls diet with CWG compared with corn-soybean meal diet even though they had the same dietary NE content. Similarly, for pigs fed the 2 low-energy treatments, a higher G:F was predicted for pigs fed the diet containing 30% DDGS, wheat middlings, and soybean hulls due to the higher dietary fat content.

The increased carcass yield, greater backfat depth, and decreased lean percentage shown in this study are common observations when diets are increased in energy density (Stahly and Cromwell., 1979; Beaulieu et al., 2009; Quiniou and Noblet, 2012). In the present study, the reduced dietary NE was associated with incorporating wheat middlings, soybean hulls, and DDGS to diets. Addition of these high-fiber ingredients increased gut fill, thus reducing carcass yield, which has been observed in several studies (Hinson et al., 2007; Asmus, 2012; Goehring, 2013) including the current results. The diet combination of DDGS, wheat middlings, and soybean hulls resulted in the lowest carcass yield compared with other diets, which also was the diet with the highest fiber content. Increasing dietary NE by adding CWG to the wheat middlings and soybean hulls diet or to the corn-soybean meal diet in this study did not improve carcass yield which agreed with the data of Asmus (2012), Baudon et al. (2003), De la Llata et al. (2001), and Salyer et al. (2012). Therefore, the increase in carcass yield with increasing dietary NE observed in the present study was mainly driven by the correlation with lower fiber content as dietary NE increased.

The interaction between energy intake and protein deposition was described by Campbell and Taverner (1988) in a linear-plateau form. The increase in energy intake results in greater protein deposition in a linear fashion until the maximum is reached where no further increase in protein deposition occurs. The addition of energy after the maximum point is then incorporated into body fat content. This relationship describes the increase in backfat depth with increasing dietary NE whereas no further improvements in loin depth were observed in our study. Therefore, pigs had sufficient intake of the low-energy diets to drive maximum protein deposition. The increased backfat depth also correlated with the reduction in carcass lean percentage with increasing dietary energy as indicated by other studies (Beaulieu et al., 2009; Quiniou and Noblet, 2012).

In the current study, pigs fed the diet with wheat middlings and soybean hulls had similar jowl IV to those fed the corn-soybean meal diet. This finding disagreed with the results from Asmus (2012) and Salyer et al. (2012) that found an increase in jowl IV when 19 to 20% wheat middlings was added to the corn-soybean meal diet. Nevertheless, 4 to 5% soybean hulls were included in the diets with wheat middlings in our study which may partly contribute to the difference in the responses. Adding CWG to the corn-soybean meal diet also resulted in a similar jowl IV to feeding corn-soybean meal diet with or without wheat middlings and soybean hulls. However, when including CWG in the wheat middling and soybean hulls diet, the jowl IV was significantly increased. A similar finding was also reported by Asmus (2012) who found an increase in jowl IV when feeding wheat middlings and DDGS where a greater response was observed when CWG was added in this diet. In addition, the increased jowl IV when including DDGS in diet in this study was consistent with other studies that documented higher unsaturated carcass fatty acids determined by IV value with increasing DDGS (Xu et al., 2010; Asmus, 2012; Salyer et al., 2012).

If the NE system truly valued the ingredient energy content correctly, the NEE should be constant among diets. In our study, NEE calculated either on live or carcass weight basis was not affected by dietary NE in both Exp. 1 and 2. The NEE on live weight basis of corn-soybean meal diet with wheat middlings and soybean hulls with and without CWG was slightly lower than the rest of diets in Exp. 1, but was similar in Exp. 2. This discrepancy might be due to the variation in the source of wheat middlings or soybean hulls between experiments that affected the energy content of these by-products. The NEE on a carcass basis was also similar across diets except for the diet containing 30% DDGS, wheat middlings, and soybean hulls that demonstrated a greater (poorer) value due to a lower carcass weight gain from a negative impact on carcass yield with feeding this diet. Thus, this may suggest that NE value of DDGS used in this study was overestimated.

The similar NEE across experimental diets suggested that the assigned NE values of ingredients used in this study which were based on NRC (2012) values except for DDGS can be used to determine NE level in the diet. Nevertheless, there was still a discrepancy when calculating NEE on carcass basis due to a negative impact of carcass yield in high-fiber diet containing DDGS.

In conclusion, the prediction equations provided a good estimation of growth rate and feed efficiency of growing-finishing pigs fed different levels of dietary NE except for the pigs fed the diet with DDGS. These predictions of growth performance can then be used to model economic value of different dietary energy strategies.

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FIGURES AND TABLES

Table 7.1 Analyzed nutrient composition of DDGS (as-fed basis)[1]

	Exp.1		Exp.2
Items	Phase 1 and 2	Phase 3	All phases
DM, %	90.3	90.0	90.1
CP, %	30.0	30.2	29.2
Crude fat, %	8.6	8.2	9.0
Calculated NE, kcal/kg	2,490	2,444	2,536
Crude fiber, %	7.2	8.3	8.1
ADF, %	9.8	10.7	13.0
NDF, %	25.3	24.8	28.6
Ash, %	4.4	4.4	4.3

[1] Samples of dried distillers grains with solubles (DDGS) were analyzed for fat content prior to each feed manufacturing to determine the net energy content (NE) from the equation:
NE (kcal/kg) = 115.011 × oil (%) + 1501.01 (Nitikanchana et al., 2013).

Table 7.2 Composition of diets (Exp. 1, phase 1; as-fed basis)[1]

NE level:	Low		Medium		High
Ingredient combinations:	DDGS[2] Wheat middlings Soybean hull	Wheat middlings Soybean hull	Corn Soybean meal	Wheat middlings Soybean hull CWG	Corn Soybean meal CWG
Ingredient, %					
Corn	23.5	47.3	68.0	43.3	64.0
Soybean meal, dehull, sol extr	19.7	24.8	28.8	25.0	29.1
DDGS	30.0	---	---	---	---
Soybean hulls	4.3	5.0	---	5.0	---
Wheat middlings	20.0	20.0	---	20.0	---
Choice White Grease	---	---	---	3.7	3.7
Monocalcium	---	0.55	0.88	0.55	0.88
Limestone	1.5	1.2	1.2	1.2	1.2
Salt	0.35	0.35	0.35	0.35	0.35
Vitamin premix[3]	0.15	0.15	0.15	0.15	0.15
Trace mineral premix[4]	0.15	0.15	0.15	0.15	0.15
L-Lys HCl	0.38	0.36	0.33	0.36	0.33
DL-Met	---	0.10	0.10	0.11	0.10
L-Thr	0.04	0.12	0.10	0.12	0.10
TOTAL	100	100	100	100	100
Calculated analysis					
Standardized ileal digestible (SID) amino acids, %					
Lys	1.14	1.14	1.14	1.14	1.14
Ile:Lys	67	59	62	59	61
Leu:Lys	160	121	130	118	128
Met:Lys	30	32	32	32	32
Met & Cys:Lys	56	56	56	56	56
Thr:Lys	61	61	61	61	61
Trp:Lys	18	18	18	18	18
Val:Lys	79	67	68	66	67
Total Lys, %	1.37	1.29	1.28	1.29	1.28
NE, kcal/kg[5]	2,262	2,269	2,434	2,434	2,599
CP, %	24.3	19.9	19.8	19.7	19.6
Crude fiber,%	5.9	4.7	2.5	4.6	2.4

ADF, %	7.6	5.9	3.5	5.8	3.4
NDF, %	20.9	16.3	8.6	16.0	8.2
Crude fat, %	4.4	2.7	2.8	6.2	6.3
Ca, %	0.68	0.66	0.67	0.66	0.67
P, %	0.58	0.62	0.57	0.61	0.56
Available P, %	0.26	0.26	0.26	0.26	0.26

[1] Phase 1 experimental diets were fed from d 0 to 9 (48- to 57-kg BW).
[2] Dried distillers grains with solubles.
[3] Provided per kg of premix: 4,409,200 IU vitamin A; 551,150 IU vitamin D3; 17,637 IU vitamin E; 1,764 mg vitamin K; 3,307 mg riboflavin; 11,023 mg pantothenic acid; 19,841 mg niacin; and 15.4 mg vitamin B12.
[4] Provided per kg of premix: 26.5 g Mn from manganese oxide, 110 g Fe from iron sulfate, 110 g Zn from zinc sulphate, 11 g Cu from copper sulfate, 198 mg I from calcium iodate, and 198 mg Se from sodium selenite.
[5] All energy levels used to calculate dietary net energy (NE) were based on NRC (2012) values except DDGS, where the energy value was calculated from its oil content: NE (kcal/kg) = 115.011 × oil (%) + 1501.01 (Nitikanchana et al., 2013).

Table 7.3 Composition of diets (Exp. 1, phase 2; as-fed basis)[1]

NE level:	Low		Medium		High
Ingredient combinations:	DDGS[2] Wheat middlings Soybean hull	Wheat middlings Soybean hull	Corn Soybean meal	Wheat middlings Soybean hull CWG	Corn Soybean meal CWG
Ingredient, %					
Corn	29.7	53.5	74.3	49.3	70.3
Soybean meal, dehull, sol extr	13.8	18.8	22.8	19.3	23.1
DDGS	30.0	---	---	---	---
Soybean hulls	4.3	5.0	---	5.0	---
Wheat middlings	20.0	20.0	---	20.0	---
Choice White Grease	---	---	---	3.8	3.8
Monocalcium	---	0.48	0.78	0.48	0.78
Limestone	1.4	1.1	1.1	1.1	1.1
Salt	0.35	0.35	0.35	0.35	0.35
Vitamin premix[3]	0.13	0.13	0.13	0.13	0.13
Trace mineral premix[4]	0.13	0.13	0.13	0.13	0.13
L-Lys HCl	0.33	0.31	0.28	0.31	0.28
DL-Met	---	0.06	0.05	0.07	0.06
L-Thr	0.02	0.09	0.07	0.09	0.08
TOTAL	100	100	100	100	100
Calculated analysis					
Standardized ileal digestible (SID) amino acids, %					
Lys	0.96	0.96	0.96	0.96	0.96
Ile:Lys	69	60	63	60	63
Leu:Lys	176	129	140	127	138
Met:Lys	32	31	31	31	31
Met & Cys:Lys	62	57	57	57	57
Thr:Lys	62	62	62	61	62
Trp:Lys	18	18	18	18	18
Val:Lys	84	69	70	69	70
Total Lys, %	1.17	1.10	1.08	1.10	1.08
NE, kcal/kg[5]	2,301	2,309	2,474	2,475	2,641
CP, %	21.9	17.5	17.4	17.3	17.2
Crude fiber,%	5.8	4.6	2.4	4.5	2.3

ADF, %	7.5	5.8	3.3	5.7	3.2
NDF, %	20.9	16.4	8.6	16.0	8.3
Crude fat, %	4.5	2.8	2.9	6.4	6.5
Ca, %	0.61	0.60	0.60	0.60	0.60
P, %	0.56	0.58	0.52	0.57	0.51
Available P, %	0.25	0.23	0.23	0.23	0.23

[1] Phase 2 experimental diets were fed from d 9 to 29 (57- to 76-kg BW).

[2] Dried distillers grains with solubles.

[3] Provided per kg of premix: 4,409,200 IU vitamin A; 551,150 IU vitamin D3; 17,637 IU vitamin E; 1,764 mg vitamin K; 3,307 mg riboflavin; 11,023 mg pantothenic acid; 19,841 mg niacin; and 15.4 mg vitamin B12.

[4] Provided per kg of premix: 26.5 g Mn from manganese oxide, 110 g Fe from iron sulfate, 110 g Zn from zinc sulphate, 11 g Cu from copper sulfate, 198 mg I from calcium iodate, and 198 mg Se from sodium selenite.

[5] All energy levels used to calculate dietary net energy (NE) were based on NRC (2012) values except DDGS, where the energy value was calculated from its oil content: NE (kcal/kg) = 115.011 × oil (%) + 1501.01 (Nitikanchana et al., 2013).

Table 7.4 Composition of diets (Exp. 1, phase 3; as-fed basis)[1]

NE level:	Low		Medium		High
Ingredient combinations:	DDGS[2] Wheat middlings Soybean hull	Wheat middlings Soybean hull	Corn Soybean meal	Wheat middlings Soybean hull CWG	Corn Soybean meal CWG
Ingredient, %					
Corn	33.1	57.0	77.8	52.8	73.8
Soybean meal, dehull, sol extr	10.6	15.7	19.7	16.1	20.0
DDGS	30.0	---	---	---	---
Soybean hulls	4.3	5.0	---	5.0	---
Wheat middlings	20.0	20.0	---	20.0	---
Choice White Grease	---	---	---	3.8	3.7
Monocalcium	---	0.45	0.75	0.45	0.75
Limestone	1.2	1.0	0.9	1.0	0.9
Salt	0.35	0.35	0.35	0.35	0.35
Vitamin premix[3]	0.10	0.10	0.10	0.10	0.10
Trace mineral premix[4]	0.10	0.10	0.10	0.10	0.10
L-Lys HCl	0.28	0.26	0.23	0.25	0.23
DL-Met	---	0.03	0.02	0.04	0.03
L-Thr	---	0.08	0.06	0.08	0.07
TOTAL	100	100	100	100	100
Calculated analysis					
Standardized ileal digestible (SID) amino acids, %					
Lys	0.84	0.84	0.84	0.84	0.84
Ile:Lys	73	62	66	62	65
Leu:Lys	193	139	152	136	149
Met:Lys	35	30	30	31	31
Met & Cys:Lys	67	59	58	59	58
Thr:Lys	64	64	64	64	64
Trp:Lys	18.5	18.5	18.5	18.5	18.5
Val:Lys	89	73	74	73	73
Total Lys, %	1.04	0.97	0.95	0.97	0.95
NE, kcal/kg[5]	2,312	2,333	2,498	2,498	2,664
CP, %	20.7	16.2	16.1	16.0	15.9
Crude fiber,%	6.1	4.6	2.3	4.5	2.2

ADF,%	7.7	5.7	3.3	5.6	3.2
NDF,%	20.8	16.4	8.7	16.1	8.4
Crude fat, %	4.5	2.9	3.0	6.4	6.5
Ca, %	0.53	0.53	0.53	0.53	0.53
P, %	0.54	0.56	0.50	0.55	0.49
Available P, %	0.25	0.22	0.22	0.22	0.22

[1] Phase 3 experimental diets were fed from d 29 to 53 (76- to 98-kg BW).
[2] Dried distillers grains with solubles.
[3] Provided per kg of premix: 4,409,200 IU vitamin A; 551,150 IU vitamin D3; 17,637 IU vitamin E; 1,764 mg vitamin K; 3,307 mg riboflavin; 11,023 mg pantothenic acid; 19,841 mg niacin; and 15.4 mg vitamin B12.
[4] Provided per kg of premix: 26.5 g Mn from manganese oxide, 110 g Fe from iron sulfate, 110 g Zn from zinc sulphate, 11 g Cu from copper sulfate, 198 mg I from calcium iodate, and 198 mg Se from sodium selenite.
[5] All energy levels used to calculate dietary net energy (NE) were based on NRC (2012) values except DDGS, where the energy value was calculated from its oil content: NE (kcal/kg) = 115.011 × oil (%) + 1501.01 (Nitikanchana et al., 2013).

Table 7.5 Composition of diets (Exp. 2, phase 1; as-fed basis)[1]

NE level:	Low		Medium		High
Ingredient combinations:	DDGS[2] Wheat middlings Soybean hull	Wheat middlings Soybean hull	Corn Soybean meal	Wheat middlings Soybean hull CWG	Corn Soybean meal CWG
Ingredient, %					
Corn	27.1	51.3	72.2	47.2	68.0
Soybean meal, dehull, sol extr	16.0	21.1	25.0	21.4	25.4
DDGS	30.0	---	---	---	---
Soybean hulls	4.7	5.0	---	5.0	---
Wheat middlings	20.0	20.0	---	20.0	---
Choice White Grease	---	---	---	3.7	3.8
Monocalcium	---	0.45	0.85	0.45	0.85
Limestone	1.4	1.2	1.1	1.2	1.1
Salt	0.35	0.35	0.35	0.35	0.35
Vitamin premix[3]	0.13	0.13	0.13	0.13	0.13
Trace mineral premix[4]	0.13	0.13	0.13	0.13	0.13
L-Lys HCl	0.31	0.29	0.27	0.29	0.26
DL-Met	---	0.06	0.05	0.07	0.06
L-Thr	---	0.08	0.07	0.08	0.07
TOTAL	100	100	100	100	100
Calculated analysis					
Standardized ileal digestible (SID) amino acids, %					
Lys	1.00	1.00	1.00	1.00	1.00
Ile:Lys	70	61	64	61	64
Leu:Lys	174	129	140	127	138
Met:Lys	32	30	31	31	31
Met & Cys:Lys	61	56	56	56	56
Thr:Lys	61	61	61	61	61
Trp:Lys	18.5	18.5	18.5	18.5	18.5
Val:Lys	84	70	71	69	70
Total Lys, %	1.22	1.14	1.13	1.14	1.13
NE, kcal/kg[5]	2,295	2,295	2,460	2,460	2,625
CP, %	22.6	18.3	18.2	18.1	18.1
Crude fiber,%	6.3	4.7	2.4	4.6	2.3

ADF,%	8.7	5.9	3.4	5.8	3.3
NDF,%	22.1	16.4	8.6	16.0	8.3
Crude fat, %	4.6	2.8	2.9	6.3	6.4
Ca, %	0.62	0.62	0.62	0.62	0.62
P, %	0.57	0.58	0.55	0.57	0.54
Available P, %	0.26	0.23	0.25	0.23	0.25

[1] Phase 1 experimental diets were fed from d 0 to 21 (57- to 77-kg BW).

[2] Dried distillers grains with solubles.

[3] Provided per kg of premix: 4,409,200 IU vitamin A; 551,150 IU vitamin D3; 17,637 IU vitamin E; 1,764 mg vitamin K; 3,307 mg riboflavin; 11,023 mg pantothenic acid; 19,841 mg niacin; and 15.4 mg vitamin B12.

[4] Provided per kg of premix: 26.5 g Mn from manganese oxide, 110 g Fe from iron sulfate, 110 g Zn from zinc sulphate, 11 g Cu from copper sulfate, 198 mg I from calcium iodate, and 198 mg Se from sodium selenite.

[5] All energy levels used to calculate dietary net energy (NE) were based on NRC (2012) values except DDGS, where the energy value was calculated from its oil content: NE (kcal/kg) = 115.011 × oil (%) + 1501.01 (Nitikanchana et al., 2013).

Table 7.6 Composition of diets (Exp. 2, phase 2; as-fed basis)[1]

NE level:	Low		Medium		High
Ingredient combinations:	DDGS[2] Wheat middlings Soybean hull	Wheat middlings Soybean hull	Corn Soybean meal	Wheat middlings Soybean hull CWG	Corn Soybean meal CWG
Ingredient, %					
Corn	32.7	57.0	77.7	52.8	73.7
Soybean meal, dehull, sol extr	10.6	15.7	19.7	16.1	20.0
DDGS	30.0	---	---	---	---
Soybean hulls	4.7	5.0	---	5.0	---
Wheat middlings	20.0	20.0	---	20.0	---
Choice White Grease	---	---	---	3.7	3.7
Monocalcium	---	0.40	0.80	0.40	0.80
Limestone	1.2	1.0	0.9	1.0	0.9
Salt	0.35	0.35	0.35	0.35	0.35
Vitamin premix[3]	0.10	0.10	0.10	0.10	0.10
Trace mineral premix[4]	0.10	0.10	0.10	0.10	0.10
L-Lys HCl	0.28	0.26	0.23	0.25	0.23
DL-Met	---	0.03	0.02	0.04	0.03
L-Thr	---	0.08	0.06	0.08	0.07
TOTAL	100	100	100	100	100
Calculated analysis					
Standardized ileal digestible (SID) amino acids, %					
Lys	0.84	0.84	0.84	0.84	0.84
Ile:Lys	73	62	66	62	65
Leu:Lys	193	139	152	136	149
Met:Lys	35	30	30	30	31
Met & Cys:Lys	67	58	58	58	58
Thr:Lys	64	64	64	64	64
Trp:Lys	18.5	18.5	18.5	18.5	18.5
Val:Lys	89	73	74	73	73
Total Lys, %	1.04	0.97	0.95	0.97	0.95
NE, kcal/kg[5]	2,332	2,332	2,496	2,496	2,661
CP, %	20.4	16.2	16.1	16.0	15.9
Crude fiber,%	6.2	4.6	2.3	4.5	2.2

ADF, %	8.5	5.7	3.3	5.6	3.2
NDF, %	22.2	16.4	8.7	16.1	8.4
Crude fat, %	4.7	2.9	3.0	6.4	6.5
Ca, %	0.55	0.55	0.55	0.55	0.55
P, %	0.54	0.55	0.51	0.54	0.51
Available P, %	0.25	0.21	0.23	0.21	0.23

[1] Phase 2 experimental diets were fed from d 21 to 44 (77- to 98-kg BW).

[2] Dried distillers grains with solubles.

[3] Provided per kg of premix: 4,409,200 IU vitamin A; 551,150 IU vitamin D3; 17,637 IU vitamin E; 1,764 mg vitamin K; 3,307 mg riboflavin; 11,023 mg pantothenic acid; 19,841 mg niacin; and 15.4 mg vitamin B12.

[4] Provided per kg of premix: 26.5 g Mn from manganese oxide, 110 g Fe from iron sulfate, 110 g Zn from zinc sulphate, 11 g Cu from copper sulfate, 198 mg I from calcium iodate, and 198 mg Se from sodium selenite.

[5] All energy levels used to calculate dietary net energy (NE) were based on NRC (2012) values except DDGS, where the energy value was calculated from its oil content: NE (kcal/kg) = 115.011 × oil (%) + 1501.01 (Nitikanchana et al., 2013).

Table 7.7 Composition of diets (Exp. 2, phase 3; as-fed basis)[1]

NE level:	Low		Medium		High
Ingredient combinations:	DDGS[2] Wheat middlings Soybean hull	Wheat middlings Soybean hull	Corn Soybean meal	Wheat middlings Soybean hull CWG	Corn Soybean meal CWG
Ingredient, %					
Corn	36.2	60.5	81.3	56.5	77.3
Soybean meal, dehull, sol extr	7.3	12.4	16.2	12.7	16.5
DDGS	30.0	---	---	---	---
Soybean hulls	4.7	5.0	---	5.0	---
Wheat middlings	20.0	20.0	---	20.0	---
Choice White Grease	---	---	---	3.7	3.7
Monocalcium	---	0.43	0.85	0.43	0.85
Limestone	1.1	0.9	0.8	0.9	0.8
Salt	0.35	0.35	0.35	0.35	0.35
Vitamin premix[3]	0.08	0.08	0.08	0.08	0.08
Trace mineral premix[4]	0.08	0.08	0.08	0.08	0.08
L-Lys HCl	0.25	0.23	0.21	0.23	0.21
DL-Met	---	0.02	0.02	0.02	0.02
L-Thr	---	0.09	0.07	0.09	0.07
TOTAL	100	100	100	100	100
Calculated analysis					
Standardized ileal digestible (SID) amino acids, %					
Lys	0.74	0.74	0.74	0.74	0.74
Ile:Lys	75	63	67	63	67
Leu:Lys	208	147	162	144	158
Met:Lys	38	31	31	30	31
Met & Cys:Lys	73	61	61	60	60
Thr:Lys	67	68	67	67	67
Trp:Lys	18.5	18.5	18.5	18.5	18.4
Val:Lys	94	76	77	75	76
Total Lys, %	0.93	0.86	0.85	0.86	0.84
NE, kcal/kg[5]	2,355	2,355	2,519	2,519	2,684
CP, %	19.1	14.9	14.7	14.7	14.5
Crude fiber,%	6.1	4.5	2.2	4.4	2.2

ADF,%	8.5	5.7	3.2	5.6	3.1
NDF,%	22.2	16.5	8.7	16.1	8.4
Crude fat, %	4.8	3.0	3.1	6.4	6.6
Ca, %	0.50	0.50	0.50	0.50	0.50
P, %	0.53	0.54	0.51	0.53	0.50
Available P, %	0.24	0.21	0.24	0.21	0.24

[1] Phase 3 experimental diets were fed from d 44 to 74 (98- to 124-kg BW).

[2] Dried distillers grains with solubles.

[3] Provided per kg of premix: 4,409,200 IU vitamin A; 551,150 IU vitamin D3; 17,637 IU vitamin E; 1,764 mg vitamin K; 3,307 mg riboflavin; 11,023 mg pantothenic acid; 19,841 mg niacin; and 15.4 mg vitamin B12.

[4] Provided per kg of premix: 26.5 g Mn from manganese oxide, 110 g Fe from iron sulfate, 110 g Zn from zinc sulphate, 11 g Cu from copper sulfate, 198 mg I from calcium iodate, and 198 mg Se from sodium selenite.

[5] All energy levels used to calculate dietary net energy (NE) were based on NRC (2012) values except DDGS, where the energy value was calculated from its oil content: NE (kcal/kg) = 115.011 × oil (%) + 1501.01 (Nitikanchana et al., 2013).

Table 7.8 Analyzed nutrient composition of experimental 1 diets (as-fed basis)[1]

NE level:	Low		Medium		High
Ingredient combinations:	DDGS[2] Wheat middlings Soybean hull	Wheat middlings Soybean hull	Corn Soybean meal	Wheat middlings Soybean hull CWG	Corn Soybean meal CWG
Phase 1					
DM	89.8	89.8	89.7	90.1	89.9
CP	23.7	23.0	19.9	20.2	19.1
Crude fat	4.4	3.8	2.9	5.6	5.8
Crude fiber	5.6	3.8	1.5	4.4	1.9
ADF	9.1	6.2	4.5	6.4	4.1
NDF	20.5	13.1	9.2	14.0	7.3
Ash	6.0	5.4	5.2	5.3	5.0
Phase 2					
DM	90.4	89.6	89.2	90.0	89.7
CP	23.5	18.1	17.4	18.1	17.0
Crude fat	4.7	2.8	3.0	5.0	5.4
Crude fiber	5.3	3.9	1.6	4.3	1.9
ADF	10.1	6.1	1.8	7.4	2.1
NDF	19.2	13.1	6.7	13.5	6.5
Ash	5.7	5.3	4.9	5.2	4.6
Phase 3					
DM	90.5	89.7	89.7	90.1	90.0
CP	21.1	16.5	17.3	17.4	17.4
Crude fat	4.9	3.0	2.7	5.2	4.5
Crude fiber	5.7	4.4	2.3	4.5	2.2
ADF	7.4	5.3	3.0	5.3	2.5
NDF	19.5	14.9	8.6	14.1	8.3
Ash	5.3	5.0	4.4	5.2	4.5

[1] Diet samples were collected from feeders during phase and stored at -20ºC, then the proximate analysis was conducted on composite samples (Ward labs, Kearney NE). Diets were fed in 3 phases from 48 to 57, 57 to 76, and 76 to 98 kg.

[2] Dried distillers grains with solubles.

Table 7.9 Analyzed nutrient composition of experimental 2 diets (as-fed basis)[1]

NE level:	Low		Medium		High
Ingredient combinations:	DDGS[2] Wheat middlings Soybean hull	Wheat middlings Soybean hull	Corn Soybean meal	Wheat middlings Soybean hull CWG	Corn Soybean meal CWG
Phase 1					
DM	89.6	88.6	88.7	89.5	89.1
CP	22.8	18.4	17.6	18.6	18.4
Crude fat	3.6	2.2	2.3	5.5	5.4
Crude fiber	5.2	4.2	1.7	4.6	2.1
ADF	7.0	5.3	2.1	5.2	2.4
NDF	17.3	13.4	6.3	13.3	5.5
Ash	5.9	5.1	4.7	5.2	4.8
Phase 2					
DM	89.8	89.2	88.9	89.5	88.9
CP	20.5	16.8	16.5	16.3	16.1
Crude fat	4.3	2.8	2.6	5.8	5.7
Crude fiber	5.7	3.9	2.0	4.7	2.3
ADF	7.1	5.0	2.3	5.5	2.2
NDF	17.6	12.8	6.7	14.4	6.5
Ash	5.3	4.9	4.1	4.4	4.1
Phase 3					
DM	90.2	89.5	89.3	89.9	87.7
CP	19.7	15.4	15.7	15.6	16.4
Crude fat	4.4	3.4	2.7	6.2	5.5
Crude fiber	5.9	4.4	2.1	5.5	2.4
ADF	7.7	5.2	1.9	6.5	2.7
NDF	17.7	15.4	7.0	16.1	7.0
Ash	5.1	4.6	2.7	4.4	3.7

[1] Diet samples were collected from feeders during phase and stored at -20ºC, then the proximate analysis was conducted on composite samples (Ward labs, Kearney NE). Diets were fed in 3 phases from 57 to 77, 77 to 98, and 98 to124 kg.

[2] Dried distillers grains with solubles.

Table 7.10 Effects of feeding different dietary net energy (NE) levels to growing-finishing pigs when dietary Lys is adequate (Exp. 1)[1]

NE level:	Low		Medium		High		Probability, $P <$		
								NE level	
Ingredient combinations[2]:	DDGS[3] Wheat middlings Soybean hull	Wheat middlings Soybean hull	Corn Soybean meal	Wheat middlings Soybean hull CWG	Corn Soybean meal CWG	SEM	TRT	Linear	Quad
Initial BW, kg	48.1	48.1	48.1	48.0	48.1	0.82	1.00	0.99	0.99
Final BW, kg	95.5[a]	98.1[ab]	98.6[b]	99.3[b]	100.1[b]	1.21	0.11	0.04	0.65
Overall period									
ADG, g	893[a]	944[b]	954[cb]	967[cb]	981[c]	11.4	0.01	0.01	0.34
95% CI[4] of ADG	869 - 916	921 - 968	929 - 980	943 - 990	958 - 1005	---	---	---	---
ADFI, g	2,498[b]	2,489[b]	2,467[b]	2,424[ab]	2,360[a]	30.3	0.02	0.01	0.53
G:F	0.358[a]	0.380[bf]	0.387[df]	0.399[c]	0.416[e]	0.004	0.01	0.01	0.91
95% CI of G:F	0.350 – 0.366	0.371 – 0.388	0.378 - 0.396	0.391 – 0.407	0.408 – 0.424	---	---	---	---
Predicted performance[5]									
ADG, g	933	936	954	954	974	---	---	---	---
G:F	0.380	0.372	0.387	0.398	0.412	---	---	---	---
Live wt NEE[6], Mcal/kg	6.44[a]	6.10[b]	6.42[ac]	6.22[bc]	6.36[ac]	0.07	0.01	0.26	0.97

[abcdef] Within a row, means without a common superscript differ ($P \leq 0.05$).
[1] A total of 273 pigs (PIC 1050 × 327; initially 48 kg BW) were used in a 53-d growing-finishing trial with 8 pigs per pen and 6 to 7 pens per treatment.
[2] The dietary treatments included 3 different levels of dietary NE by adding low-energy ingredients (wheat middlings or soybean hulls), 30% dried distillers grains with solubles, or choice white grease to a corn-soybean meal base diet. The difference of dietary NE content between high vs. medium and medium vs. low energy was 166 kcal/kg across all phases of feeding.
[3] Dried distillers grains with solubles.
[4] 95% confidence interval.
[5] The prediction equations used were [ADG (g/day) = 0.1135 × NE (kcal/kg) + 8.8142 × Average BW (kg) – 0.05068 × Average BW (kg) × Average BW (kg) + 275.99; G:F = 0.000096 × NE (kcal/kg) – 0.0025 × Average BW (kg) + 0.003071 × fat (%) + 0.3257] were used to calculate predicted ADG and G:F. The difference between predicted and actual growth performance of pigs fed corn-soybean meal diet was used to adjust the intercept of the prediction equations thus adjusting the growth performance of the other pens fed the other diets.
[6] Net energy caloric efficiencies (NEE) were calculated on a pen basis by multiplying total feed intake by the dietary NE concentration and dividing by total live or carcass weight gain. The carcass weight gain was obtained from subtracting HCW with the initial carcass weight by assuming 75% carcass yield across diet.

Table 7.11 Effects of feeding different dietary net energy (NE) levels to growing-finishing pigs when dietary Lys is adequate (Exp. 2)[1]

NE level:	Low		Medium		High		Probability, $P <$		
								NE level	
Ingredient combinations[2]:	DDGS[3] Wheat middlings Soybean hull	Wheat middlings Soybean hull	Corn Soybean meal	Wheat middlings Soybean hull CWG	Corn Soybean meal CWG	SEM	TRT	Linear	Quad
Initial BW, kg	56.8	56.8	56.8	56.8	56.8	0.98	1.00	0.99	1.00
Final BW, kg	121.8^{a}	123.2^{a}	125.1^{ab}	123.9^{a}	128.3^{b}	1.28	0.02	0.01	0.46
Overall period									
ADG, g	879^{a}	888^{ab}	923^{b}	905^{ab}	963^{c}	12.4	0.01	0.01	0.43
95% CI[4] of ADG	853 - 904	863 - 914	895 - 950	880 - 930	937 - 988	---	---	---	---
ADFI, g	2,667^{a}	2,620^{ab}	2,603^{ab}	2,512^{b}	2,562^{ab}	40.6	0.11	0.11	0.25
G:F	0.330^{a}	0.339^{a}	0.355^{b}	0.360^{b}	0.376^{c}	0.004	0.01	0.01	0.58
95% CI of G:F	0.321 – 0.338	0.331 – 0.348	0.345 – 0.364	0.352 – 0.369	0.367 – 0.385	---	---	---	---
Predicted performance[5]									
ADG, g	907	904	923	924	938	---	---	---	---
G:F	0.350	0.340	0.355	0.368	0.376	---	---	---	---
Carcass wt, kg	87.5^{a}	89.7^{ab}	91.7^{bc}	90.2^{b}	94.2^{c}	0.93	0.01	0.01	0.62
Yield, %	72.4^{a}	73.4^{bd}	74.0^{dc}	73.2^{b}	74.3^{c}	0.22	0.01	0.01	0.90

Backfat[6], mm.	15.2[a]	16.4[b]	17.8[c]	17.1[bc]	19.4[d]	0.42	0.01	0.01	0.73
Loin depth, mm.	62.3[ab]	61.3[ab]	62.6[a]	61.8[ab]	60.6[b]	0.53	0.13	0.18	0.05
Lean, %	55.0[a]	54.2[b]	54.0[b]	54.1[b]	53.1[c]	0.18	0.01	0.01	0.20
Jowl IV	74.3[c]	70.1[a]	69.6[a]	71.6[b]	70.4[a]	0.42	0.01	0.01	0.08
Live wt NEE[7], Mcal/kg	7.09	6.88	7.04	6.94	7.08	0.09	0.35	0.36	0.60
Carcass NEE, Mcal/kg	10.27[a]	9.61[b]	9.79[b]	9.76[b]	9.79[b]	0.15	0.05	0.43	0.52

[abcd]Within a row, means without a common superscript differ ($P \leq 0.05$).

[1] A total of 271 pigs (PIC 1050 × 327; initially 57 kg BW) were used in a 74-d growing-finishing trial with 7 to 8 pigs per pen and 6 to 7 pens per treatment.

[2] The dietary treatments included 3 different levels of dietary NE by adding low-energy ingredients (wheat middlings or soybean hulls), 30% dried distillers grains with solubles, or choice white grease to a corn-soybean meal base diet. The difference of dietary NE content between high vs. medium and medium vs. low energy was 166 kcal/kg across all phases of feeding.

[3] Dried distillers grains with solubles.

[4] 95% confidence interval.

[5] The prediction equations from the meta-analysis [ADG (g/day) = 0.1135 × NE (kcal/kg) + 8.8142 × Average BW (kg) – 0.05068 × Average BW (kg) × Average BW (kg) + 275.99; G:F = 0.000096 × NE (kcal/kg) – 0.0025 × Average BW (kg) + 0.003071 × fat (%) + 0.3257] were used to calculate predicted ADG and G:F. The difference between predicted and actual growth performance of pigs fed corn-soybean meal diet was used to adjust the intercept of the prediction equations thus adjusting the growth performance of the other pens fed the other diets.

[6] Backfat, loin depth, and lean percentage were adjusted to a common HCW.

[7] Net energy caloric efficiencies (NEE) were calculated on a pen basis by multiplying total feed intake by the dietary NE concentration and dividing by total live or carcass weight gain. The carcass weight gain was obtained from subtracting HCW with the initial carcass weight by assuming 75% carcass yield across diet.