Energy and amino acid sources and levels for nursery and finishing swine diets

by

Rafe Quinnlan Royall

B.S., Texas Tech University, 2020
M.S., Kansas State University, 2022

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Animal Sciences and Industry
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2024

Abstract

The 5 chapters of this dissertation involve 1) determining the effects of dietary net energy (NE) concentrations on growth performance and carcass characteristics of finishing pigs and an evaluation of the accuracy of different ingredient databases and NE equations, 2) determining standardized ileal digestible (SID) threonine:lysine (Thr:Lys) requirement estimates for 11 to 120 kg pigs, 3) a review of dietary soybean meal (SBM) usage in growing and finishing pig diets, 4) evaluating the effects of 3 lactation feeder designs on sow and litter performance, and 5) determining the effects of replacing lactose with novel carbohydrate sources on nursery pig growth performance and feed intake preference. Chapter 1 utilized 1,927 finishing pigs to determine the effects of reducing NE and using this caloric efficiency (CE) data to estimate the accuracy of ingredient databases and NE equations. Results from this experiment suggest that reducing NE reduces finishing pig performance, the NE values from the CVB database and system of equations are the most accurate estimate of NE when CE is calculated based on live gain, while the values from the Brazilian Tables for Poultry and Swine are the most accurate when CE is calculated based on carcass gain. Chapter 2 consisted of 4 experiments involving 3,208 pigs were conducted to determine SID Thr:Lys ratio requirement estimates for average daily gain (ADG), gain to feed ratio (G:F), and blood urea nitrogen (BUN) throughout the late nursery, grower, and finisher phases. Dose-response models developed using the data from Exp. 1 and 2 predicted a requirement for ADG beyond the highest dose tested (68% SID Thr:Lys ratio), which led us to test a wider range of SID Thr:Lys ratios in Exp. 3 and 4. Data from Exp. 3 and 4 were combined and used to fit dose-response models which suggested that; ADG was maximized between 61.1 and 68.6% SID Thr:Lys ratio, G:F is increased up to 59.2% SID Thr:Lys with no improvement thereafter, and BUN was minimized at 69.2%. Additionally, these data may suggest that SID Thr:Lys requirements are similar for pigs from 37 to 70 kg and 96 to 120 kg. Chapter 3 consisted of a literature review over dietary SBM levels in various dietary and environmental situations. Soybean meal is a good source of amino acids and energy in the diet and contains biologically active compounds that can improve swine health and growth performance. Chapter 4 consisted of one experiment utilized 557 mixed parity sows to evaluate lactation feeder design on sow and litter performance, feeder cleaning criteria, and economic return. We observed that sows fed using the wet-dry feeder designs had increased feed disappearance with no effects on sow and litter performance compared to dry feeders, thus worsening litter feed efficiency and increasing feed cost per sow and litter. Chapter 5 consisted of 2 experiments which used 660 nursery pigs to determine the effect of replacing lactose in nursery pig diets with one of two novel carbohydrate products (CHO-D and CHO-L) on growth performance and feed intake preference. In Exp. 1, we found similar growth performance between all carbohydrate sources, but we were unable to detect benefits of adding lactose to the diet. In Exp. 2, we found that pigs preferred the diet containing CHO-D over the diet containing lactose in phase 1, but the inverse was true in phase 2. However, pigs preferred the diet containing lactose over the diet containing CHO-L in all phases. Thus, we could not determine whether the novel carbohydrate products are suitable replacements for lactose.

Energy and amino acid sources and levels for nursery and finishing swine diets

by

Rafe Quinnlan Royall

B.S., Texas Tech University, 2020
M.S., Kansas State University, 2022

A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Animal Sciences and Industry
College of Agriculture

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2024

Approved by:	Approved by:
Co-Major Professor Dr. Joel DeRouchey	Co-Major Professor Dr. Robert Goodband

Copyright

Abstract

The 5 chapters of this dissertation involve 1) determining the effects of dietary net energy (NE) concentrations on growth performance and carcass characteristics of finishing pigs and an evaluation of the accuracy of different ingredient databases and NE equations, 2) determining standardized ileal digestible (SID) threonine:lysine (Thr:Lys) requirement estimates for 11 to 120 kg pigs, 3) a review of dietary soybean meal (SBM) usage in growing and finishing pig diets, 4) evaluating the effects of 3 lactation feeder designs on sow and litter performance, and 5) determining the effects of replacing lactose with novel carbohydrate sources on nursery pig growth performance and feed intake preference. Chapter 1 utilized 1,927 finishing pigs to determine the effects of reducing NE and using this caloric efficiency (CE) data to estimate the accuracy of ingredient databases and NE equations. Results from this experiment suggest that reducing NE reduces finishing pig performance, the NE values from the CVB database and system of equations are the most accurate estimate of NE when CE is calculated based on live gain, while the values from the Brazilian Tables for Poultry and Swine are the most accurate when CE is calculated based on carcass gain. Chapter 2 consisted of 4 experiments involving 3,208 pigs were conducted to determine SID Thr:Lys ratio requirement estimates for average daily gain (ADG), gain to feed ratio (G:F), and blood urea nitrogen (BUN) throughout the late nursery, grower, and finisher phases. Dose-response models developed using the data from Exp. 1 and 2 predicted a requirement for ADG beyond the highest dose tested (68% SID Thr:Lys ratio), which led us to test a wider range of SID Thr:Lys ratios in Exp. 3 and 4. Data from Exp. 3 and 4 were combined and used to fit dose-response models which suggested that; ADG was maximized between 61.1 and 68.6% SID Thr:Lys ratio, G:F is increased up to 59.2% SID Thr:Lys with no improvement thereafter, and BUN was minimized at 69.2%. Additionally, these data may suggest that SID Thr:Lys requirements are similar for pigs from 37 to 70 kg and 96 to 120 kg. Chapter 3 consisted of a literature review over dietary SBM levels in various dietary and environmental situations. Soybean meal is a good source of amino acids and energy in the diet and contains biologically active compounds that can improve swine health and growth performance. Chapter 4 consisted of one experiment utilized 557 mixed parity sows to evaluate lactation feeder design on sow and litter performance, feeder cleaning criteria, and economic return. We observed that sows fed using the wet-dry feeder designs had increased feed disappearance with no effects on sow and litter performance compared to dry feeders, thus worsening litter feed efficiency and increasing feed cost per sow and litter. Chapter 5 consisted of 2 experiments which used 660 nursery pigs to determine the effect of replacing lactose in nursery pig diets with one of two novel carbohydrate products (CHO-D and CHO-L) on growth performance and feed intake preference. In Exp. 1, we found similar growth performance between all carbohydrate sources, but we were unable to detect benefits of adding lactose to the diet. In Exp. 2, we found that pigs preferred the diet containing CHO-D over the diet containing lactose in phase 1, but the inverse was true in phase 2. However, pigs preferred the diet containing lactose over the diet containing CHO-L in all phases. Thus, we could not determine whether the novel carbohydrate products are suitable replacements for lactose.

Table of Contents

List of Figures

List of Tables

Acknowledgements

Chapter 1. Appreciation is expressed to SVC Research (St. Peter, MN) for providing the animals and research facility, and to Genus PIC for technical support.

Chapter 2. Appreciation is expressed to SVC Research (St. Peter, MN) for providing the animals and research facility, and to Genus PIC for technical support for Exp. 1 and 2.

Chapter 4. We would like to thank the farm staff at the JBS Stateline 2 farm (Dalhart, TX).

Chapter 5. Appreciation is expressed to Cargill Starches, Sweeteners, & Texturizers and Oxford Nutrition Consulting, LLC for technical support for each experiment.

Chapter 1 - Dietary net energy concentrations on growth performance and carcass characteristics of finishing pigs and evaluation of the accuracy of different ingredient databases and net energy equations

Abstract

This study evaluated the effect of reducing dietary NE on growth performance and carcass characteristics of finishing pigs and determined which of 8 NE estimates were most accurate in predicting these responses. A total of 1,927 pigs (initially 23.3 ± 0.23 kg) were fed 1 of 5 diets with decreasing NE based on Eq. 1-8 NRC (2012) using analysis of major ingredients. A corn-soybean meal-based control diet was blended with a low energy diet containing 8% less NE achieved through inclusion of 25% wheat middlings and 15% corn distillers dried grains with solubles (DDGS; 6% oil) to achieve intermediate NE concentrations. Decreasing NE decreased (linear, $P < 0.001$) ADG and final BW and increased (linear, $P <0.001$) ADFI, resulting in decreased (linear, $P < 0.001$) G:F. When caloric efficiency (CE) was calculated on a live gain basis, decreasing NE worsened (linear, $P < 0.001$) CE based on NRC (2012) ingredient NE values and when NE was calculated using NRC (2012) Eq. 1-8 using the DE values from the NRC ingredient database (NRC 2), but improved (linear, $P \leq 0.004$) CE calculated based on INRA (2008) or Brazilian Tables for Poultry and Swine (2024) values or when based on an average of NRC (2012) Eq. 1-7 and 1-8 (NRC 1) or INRA equations. However, when using CVB (2020) values or equations, decreasing NE did not affect CE based on live gain. When CE is calculated based on a carcass gain basis, decreasing NE worsened (linear, $P \leq 0.004$) CE based on NRC or CVB ingredient values and the NRC 2 or CVB equations, but improved (linear, $P <$

0.001) CE based on INRA ingredient values or equations, or NRC 1 equations. However, when using ingredient values from the Brazilian Tables, reducing NE did not affect CE based on carcass gain. These results suggest that the NRC database and NRC 2 equation overestimate the NE of the low NE diets used in this experiment. The INRA database, NRC 1 and INRA equations underestimate their NE, whether CE is calculated based on live or carcass gain. The NE values in the CVB database, and those derived from the CVB equation appear to assess nutrient values more accurately for NE based on live gain but overestimate their value on a carcass basis. The Brazilian tables appear to underestimate the low NE diets on a live basis, but more accurately value them on a carcass basis. Reducing diet NE resulted in linear reductions in ADG and G:F with variability observed in the accuracy of different NE systems used to predict energetic efficiency.

Key Words: Caloric efficiency, energy, feed efficiency, finishing pigs, growth, net energy

Introduction

Feed represents the greatest portion of the cost of production in swine operations, and energy is the greatest component of these feed costs accounting for 70%, or more, of the total feed cost (Noblet and van Milgen, 2004; Noblet et al., 2022). It is well understood that increasing dietary energy improves growth performance of finishing pigs, but it simultaneously increases diet cost (Patience et al., 2006; De la Llata et al., 2007). Feeding high energy diets has been re-evaluated in recent years due to the increasing cost of energy-dense ingredients (i.e., corn and fat sources) in the United States resulting from increased demand for ethanol and other biofuels. As a result, the use of lower energy diets is more common than in the past. Feeding low-energy diets decreases G:F ratio (Nitikanchana et al., 2015) but the effects on ADG are variable (Coble et al., 2018; Zhao et al., 2023; Hagen et al., 2023). The variation in ADG may be due to chemical composition, i.e., neutral detergent fiber (NDF), of various low-energy ingredients (i.e., dried distillers grains with solubles). A high NDF content has been observed to limit ADFI, hence ADG, due to filling gastric capacity (Stein and Easter, 1996). Therefore, it is important to determine the extent of this decrease in growth performance when feeding low-energy diets in modern pigs.

There are multiple reference sources and equations to estimate the NE content of diets and determining the accuracy of these are important for nutritionists to precisely formulate diets to a specific NE content. Ingredient databases found in the EvaPig software (INRA, 2008), the NRC (2012), and the Brazilian Tables for Poultry and Swine (2024) are all based on equations developed by Noblet et al. (1994), but differ in the chemical analysis of ingredients, and metabolizable energy (ME) values used as a starting point. However, the Central Bureau Livestock Feeding (CVB, 2020) derived their NE values based on equations developed by Blok et al. (2006, 2015) which consider the enzymatically digestible and fermentable fractions of total digestible carbohydrates. This results in a greater estimate of NE for fiber-dense ingredients compared to the equations developed by Noblet et al. (1994).

Traditionally, NE of individual ingredients and complete diets have been measured using the indirect calorimetry method. However, this process requires highly specialized equipment and may not accurately depict the response of pigs reared in a commercial environment, considering the dramatic differences in stressors (i.e., environmental and health related). As such, using caloric efficiency (CE) to estimate the NE of a test ingredient, or diet, in relation to a known ingredient has gained some traction amongst swine nutritionists (Boyd et al., 2010;

Estrada et al., 2017; Cemin et al., 2020). This allows estimation of the productive energy of an ingredient or diet under commercial conditions.

Our objective of this study was to evaluate the effect of dietary NE on growth performance and carcass characteristics of finishing pigs. Our second objective was to utilize CE to evaluate the accuracy of different ingredient databases and NE equations.

Materials and Methods

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment (IACUC #4525). The study was conducted in a commercial research facility located in south-central Minnesota (Swine Vet Center, St. Peter, MN). The barn had slatted concrete flooring, deep pits for manure storage, and was naturally ventilated. Pens (3 × 5.5 m) contained a 3-hole stainless steel dry self-feeder (Thorp Equipment, Thorp, WI) and a 1-cup waterer to provide *ad libitum* access to feed and water. Daily feed additions to each pen were accomplished using a robotic feeding system (FeedPro, Feedlogic Corp., Wilmar, MN) able to record feed amounts for individual pens. All treatment diets were manufactured at the United Farmers Cooperative Feed Mill (Klossner, MN) and were fed in meal form.

Animals and Diets

A total of 1,927 pigs (337 × 1050 PIC, Hendersonville TN; initially 23.3 ± 0.23 kg) were used. Pens of pigs were blocked by initial BW and randomly allotted to 1 of 5 dietary treatments in a randomized complete block design. There were 23 to 26 mixed-sex pigs per pen and 15 replications per treatment. The high energy diet (Control) was corn-soybean meal-based. Using analysis of the major ingredients (Table 1.1) and Eq. 1-8 NRC (2012), the low energy diet contained 8% less NE than the Control diet through the inclusion of 25% wheat middlings and

15% corn distillers dried grains with solubles (DDGS; 6% oil; Tables 1.2 and 1.3). These diets were then blended to achieve the intermediate NE levels (2, 4, and 6% less NE than the Control diet). Diets were fed by phase and the approximate weight range of pigs for each phase was 20 to 40, 40 to 60, 60 to 80, 80 to 104, and 104 to 133 kg. The high and low NE diets were blended to meet the target NE values for each treatment diet in phase 1, while 3 base diets with the high, middle, and low NE values were blended to meet target NE values for each treatment diet in all other phases (Tables 1.2 and 1.3). All diets were formulated to meet or exceed NRC (2012) requirement estimates and were maintained at a constant SID Lys:NE ratio. To determine ADG, ADFI, G:F, and CE, pens of pigs were weighed, and feed disappearance was recorded at dietary phase changes and at an intermediate time point within dietary phases throughout the trial. On d 99, the heaviest pigs (up to 5) per pen were marketed to equalize inventory to 21 pigs for all pens. On d 111, the heaviest 3 to 4 pigs per pen were marketed and the remaining pigs were marketed on d 125, at the conclusion of the study.

At each marketing event, pigs were individually weighed and transported to a commercial abattoir (JBS, Worthington, MN) for carcass data collection. All pigs were given an RFID ear tag at weaning and individual identification was used to track carcass data. Measurements including hot carcass weight (HCW), loin depth, backfat depth, and carcass percentage lean were collected. The calculation for carcass yield was individual pig HCW at the packing plant divided by individual final pig weight on the farm.

Dietary NE values were used to calculate CE on a live- and carcass-weight basis. To assess the accuracy of different ingredient databases, dietary NE was calculated based on reported NE loading values for corn, soybean meal, corn DDGS, and wheat middlings derived from 8 different sources. Four sources were ingredient databases; 1) NRC (2012; chapter 17); 2)

EvaPig (2008; INRA); 3) CVB (2020); and 4) the Brazilian Tables for Poultry and Swine (2024; Brazilian Tables). For the other 4 sources, NE was calculated using the analysis of the major ingredients based on the following equations; 1) an average of NRC (2012) Eq. 1-7 and 1-8 using proximate analysis values (NRC 1); 2) NRC Eq. 1-8, utilizing DE values from the NRC ingredient database (NRC 2); 3) EvaPig software (2008; INRA), and 4) CVB feedstuff database webapp (2020; CVB). Net energy prediction Eq. 1-7 and 1-8 derived from the NRC (2012) are listed below:

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

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

Where ME is metabolizable energy, EE is ether extract, CP is crude protein, ADF is acid detergent fiber, and DE is digestible energy.

Chemical Analysis

Prior to diet formulation, representative samples of corn, soybean meal, corn DDGS, and wheat middlings were submitted for proximate analysis, and analysis of starch, ADF, NDF, and amino acids. (Table 1.1). These nutrient values were then used to determine NE based on the equations from the various systems. Diet samples were collected from feeders during every phase and stored at -20°C until chemical analysis. Subsamples of each diet for each dietary phase were ground to create a homogenous sample and then submitted for proximate analysis and complete AA profiles (Table 1.4). Standard procedures (AOAC International, 2006) were followed for analysis of amino acid content (method 982.30), moisture (method 934.01), CP

(990.03), ether extract (method 920.39), crude fiber (method 978.10), ash (method 942.05), acid detergent fiber and NDF (Van Soest et al., 1991), and starch.

Statistical Analysis

Data were analyzed as a randomized complete block design for one-way ANOVA using the lmer function from the lme4 package in R Studio (Version 3.5.2, R Core Team; Vienna, Austria). Pen was considered the experimental unit, initial BW served as a blocking factor, and treatment served as the fixed effect in the statistical model. Individual pig carcass data were used in the analysis using pen as a random intercept to account for subsampling of multiple carcass observations within each experimental unit. Hot carcass weight served as a covariate for loin depth, backfat depth, and percentage lean. Linear and quadratic contrast coefficients were constructed within dietary NE values. Total removals and mortality were reported and data were analyzed assuming a binomial distribution with a logit link function. Results were considered significant with $P \leq 0.05$ and marginally significant with $P \leq 0.10$.

Results

Growth and carcass performance

Decreasing NE decreased (linear, $P < 0.001$) BW on d 22 and all subsequent periods and marketing events (Table 1.5). The BW response also tested quadratic ($P < 0.05$) on d 22 through d 43 and tended to be quadratic ($P = 0.058$) on d 66 with the BW decreasing to a greater extent as the percentage of NE reduction increased. During phase 1 (d 0 to 22), decreasing NE decreased (quadratic, $P < 0.001$) ADG and (linear, $P < 0.001$) ADFI, resulting in decreased (quadratic, $P < 0.001$) G:F. The quadratic response was because ADG and G:F were reduced to a greater extent as NE was reduced by 4 to 8% than by the first 4% reduction. During phases 2 through 5 (d 22 to 43, 43 to 66, 66 to 90, and 90 to 125, respectively) decreasing NE decreased (linear, $P \leq 0.001$) ADG and increased (linear, $P \leq 0.015$) ADFI, resulting in decreased (linear, $P < 0.001$) G: F. Decreasing NE decreased (linear, $P < 0.001$) daily SID Lys intake in phases 1, 3, 4, 5, and overall; however SID Lys intake/d increased (linear, $P < 0.001$) with decreasing NE in phase 2. In phase 1 (d 0 to 22) decreasing NE decreased (quadratic, $P < 0.001$) SID Lys intake/kg of gain, but in phases 2, 5, and overall decreasing NE increased (linear, $P \leq 0.006$) SID Lys intake/kg of gain. Decreasing NE decreased (linear, $P < 0.001$) daily NE intake in phases 1, 3, 4, 5, and overall; however, NE intake/d increased (linear, $P < 0.001$) with decreasing NE in phase 2. Throughout the overall experiment (d 0 to 125), decreasing NE decreased (linear, $P < 0.001$) ADG on a live- and carcass- weight basis and increased (linear, $P < 0.001$) ADFI, resulting in decreased (linear, $P < 0.001$) G:F on a live- and carcass-weight basis. In addition, reducing NE tended to increase (linear, $P = 0.073$) percentage of pig removals, with no evidence of difference ($P > 0.10$) on mortality, or total removals and mortality.

For carcass characteristics, decreasing NE decreased (linear, $P \leq 0.001$) HCW, backfat depth, and carcass yield within and across marketing events (d 99, 111, 125, and overall; Table 1.6). However, decreasing NE increased (linear, $P < 0.001$) carcass lean percentage at all marketing events. Reducing NE had no affect ($P > 0.10$) on loin depth at any marketing event.

Caloric Efficiency

Caloric efficiency was calculated using NE values derived from the NRC, INRA, CVB, and the Brazilian Tables ingredient databases (Table 1.7). Overall (d 0 to 125), decreasing NE worsened (linear, $P < 0.001$) CE based on the NRC ingredient database, and improved (linear, $P \leq 0.004$) CE based on the INRA or Brazilian Tables ingredient databases. However, using the CVB ingredient database, decreasing NE resulted in no evidence of difference ($P > 0.10$) in CE. When considering CE on a carcass gain basis, decreasing NE worsened (linear, $P \leq 0.004$) CE based on the NRC or CVB loading databases, while decreasing NE improved (linear, $P < 0.001$) CE based on the INRA loading database. However, decreasing NE resulted in no evidence of difference ($P > 0.10$) in CE based on the Brazilian Tables ingredient database.

Net energy values were also calculated by utilizing analyzed ingredient values within equations from the NRC 1, NRC 2, INRA, and CVB. These NE values were then utilized to calculate CE. Overall (d 0 to 125), decreasing NE improved (linear, $P < 0.001$) CE when NE was calculated based on NRC 1 or INRA equations, but worsened (linear, $P < 0.001$) CE when NE was calculated utilizing NRC 2 values. However, when NE is calculated utilizing CVB equations, decreasing NE showed no evidence of difference ($P > 0.10$) in CE. When considering CE on a carcass gain basis, decreasing NE improved (linear, $P < 0.001$) CE when NE is calculated using NRC 1 and INRA equations. However, when NE values are calculated utilizing NRC 2 values or CVB equations, decreasing NE worsened (linear, $P \leq 0.002$) CE.

Discussion

Depending on ingredient prices, pork producers and swine nutritionists alter dietary NE to optimize growth performance and feed cost. Government legislation has increased the demand for corn to produce ethanol, and soybean oil and other fat sources for biofuel production (EPA, 2024). As a result, added fats and oils are less economically justified to use in most finishing pig diets and the swine industry has shifted towards greater implementation of low-energy, high-fiber, diets. While it is understood that reducing NE reduces gain-to-feed ratio and growth performance, the literature is inconsistent in the extent of this reduction. This is largely driven by differences in feed intake when feeding low-energy diets. Henry (1985) established that energy density of the diet is the primary determinant of ADFI, as pigs will attempt to adjust feed intake to reach a certain level of energy intake. However, this is not true in all situations. Black et al.

(1986) observed that gut capacity is a limiting factor for growth performance in pigs weighing less than 40 kg. Additionally, a review by Nyachoti et al. (2004) summarized that feed intake is affected by numerous husbandry conditions (i.e., stocking density, feeder space, and ambient temperature), and as such pigs fed in commercial environments are often unable to consume enough feed to meet their maximum growth potential. Our results would support these findings as during phase 1 (23- to 40-kg) reducing NE, by increasing dietary fiber content, reduced feed intake, but when pigs exceeded 40 kg ADFI increased with decreasing dietary NE. However, in all phases, except phase 2 (d 22 to 43), when NE reduction exceeded 4%, pigs were unable to consume adequate amounts of feed to reach a similar NE intake. This may have been a result of neutral detergent fiber (NDF) exceeding 12%, as excess NDF has been shown to limit feed intake (Graham et al., 2014a; Lerner et al., 2020a, b). A second possible explanation could be that increased bulk of high-fiber (low energy) diets may reduce feeding motivation by increasing mastication time and stimulating mechanoreceptors in the gastrointestinal tract which would limit meal size by stimulating satiety (de Leeuw et al., 2008). In our study, the inability of pigs fed diets with reduced NE to maintain NE intake appears to be the primary factor responsible for the observed reduction in growth performance.

A meta-analysis conducted by Nitikanchana et al. (2015) provided regression equations to predict growth rate and feed efficiency of growing-finishing pigs. Using the equations developed in their meta-analysis we predicted that for every 1% reduction in NE, ADG would decrease by 0.32%, while G:F was projected to decrease by 0.17%. In our study we observed that ADG decreased by 1.05%, while G:F decreased by 1.37% for every 1% reduction in NE. The majority of papers (24 out of 30) used by Nitikanchana et al. (2015) to develop the regression equations studied diets with greater than 2,300 NE, kcal/kg, whereas in our study the two lowest

NE diets were below this level. Thus, predicting performance of pigs consuming the low energy diets in our experiment may have exceeded the range of values for equations developed by Nitikanchana et al. (2015). A key component in the equations of Nitikanchana besides dietary NE is dietary fat. In most of the papers used by Nitikanchana et al. (2015), diets with higher NE would have also contained higher dietary fat. In our study, the dietary fat was actually higher in the lowest NE diet (3.6%) than in the highest NE diet (2.6%). This contributed to the relatively low change in ADG and G:F predicted when using the Nitikanchana et al. (2015) equation.

Nitikanchana et al. (2015) observed an interaction between NE and SID Lys on ADG in their meta-analysis, indicating that the response to changing NE is directly related to maintaining SID Lys above the pig's requirements. Similarly, Marçal et al. (2019) observed that increasing NE while maintaining a constant SID Lys:NE ratio increased ADG, while increasing NE without altering SID Lys did not change ADG. This is primarily due to the reduced ADFI often seen when increasing NE in the diet, as this will reduce the Lys intake/d, which could cause the pig to fall below their requirement. Because constant SID Lys:NE ratios were maintained within phase, we observed that SID Lys intake/d was linearly reduced with reducing NE. However, overall, SID Lys intake/d did not fall below NRC (2012) or PIC (2021) requirement estimates for pigs fed any dietary treatment. The SID Lys intake/kg of gain also increased linearly with decreasing NE. Pigs are most efficient at utilizing Lys when they are below their requirement (Gahl et al., 1995), therefore the increase in SID Lys intake/kg of gain in our experiment would suggest that pigs fed all dietary treatments were above their requirement for lysine.

Feeding high fiber, low NE, diets increases gut fill and visceral organ weight, thus reducing carcass yield (Asmus et al., 2014; Nemechek et al., 2015; Coble et al., 2018). The reduction in carcass yield, along with reduced live weight, resulted in the reduction in HCW observed in our study. In addition, feeding high fiber, low energy, diets decreases backfat depth and improves carcass lean, similar to our results (Just, 1982; Salyer et al., 2012; Nitikanchana et al., 2015).

It has long been understood that NE is the most accurate measure of energy utilization within the pig as it considers differences in metabolic utilization and heat increment of various nutrients. However, NE is difficult to measure and as such there are few estimates of NE available for many byproduct ingredients, and even so these may not accurately account for the variability of chemical composition found in such ingredients (Nitikanchana et al., 2015). Because of these inaccuracies, there have been several ingredient databases developed to estimate the NE of ingredients in hopes of accounting for the variation in chemical composition between regions and over time. Several of these databases (INRA, 2008; NRC, 2012; Brazilian Tables, 2024) are based on the NE prediction equation developed by Noblet et al. (1994) and modified by Sauvant et al. (2004). As such the differences in NE values listed in these databases are solely due to differences in chemical composition used as a starting point in their calculations. The chemical composition data used in the EvaPig software (INRA, 2008) was taken from chemical analysis of ingredients conducted at INRAE, which was updated most recently in 2020. Meanwhile, the data summarized in NRC (2012) was taken from a variety of published sources collected from a review of the literature from 1997 to 2012. The chemical composition data found in the Brazilian Tables (2024) were summarized from animal trials and chemical analyses conducted in Brazil. The database developed by the CVB (2020) was based on equations developed by Blok et al. (2006, 2015), which consider the enzymatically digestible and fermentable fractions of total digestible carbohydrates, thus giving a greater estimation of NE for fiber-dense ingredients compared to the equations developed by Noblet et al. (1994). The chemical composition of ingredients in the CVB database is based on data that has been continuously collected since 1985. Regardless of these differences, NE values for corn is relatively consistent among these databases ranging from 2,667 to 2,709 kcal/kg (Brazilian Tables vs. INRA), and as such it is often used as a base for the determination of NE for other ingredients. Whereas the other major ingredients used in our study (soybean meal, wheat middlings, and corn DDGS) have much more varied NE estimations; 1,975 to 2,109 kcal/kg, 1,639 to, 2,113 kcal/kg, and 1,970 to 2,343 kcal/kg, for soybean meal, wheat middlings, and corn DDGS, respectively. Fiber-dense ingredients are the most variable in their reported NE valuation, explaining the great deal of variation in the NE estimation for low-energy diets in our study.

Utilizing CE can help compare the accuracy of the various ingredient databases and systems of equations for NE calculations. If a system correctly values the NE of a test ingredient, CE values should be similar among diets, while an improvement in CE suggests that the NE of the diet is underestimated and a worsened CE would suggest that the NE of the diet is overestimated (Graham et al., 2014b; Cemin et al., 2020). Therefore, calculating CE by using the NE values derived from multiple ingredient databases can allow us to compare their accuracy at estimating NE of low energy diets.

When using ingredient NE derived from database values to calculate NE of our diets, we observed that CE based on live weight ADG was worsened as NE reduced based on the values obtained from the NRC (2012). Meanwhile, using database values from INRA (2008) or the Brazilian Tables (2024), CE improved with reducing net energy. However, there was no difference observed when CE was calculated based on NE values obtained from the CVB (2020). These results would suggest that the NRC (2012) overestimates NE of the low-energy diets used in our experiment, while both INRA (2008) and Brazilian Tables (2024) underestimate their NE, but CVB (2020) appears to be the most accurate. When CE is calculated based on carcass weight ADG, results were similar to those based on live ADG for the NRC (2012) and INRA (2008). However, when carcass CE was calculated using CVB (2020) loading values, CE worsened, suggesting that the CVB (2020) slightly overestimates NE of low energy diets. However, there was no difference observed when CE was calculated based on NE values taken from the Brazilian Tables (2024), suggesting that this ingredient database is the most accurate estimate of NE based on carcass caloric efficiency.

A second method of estimating the NE value of individual ingredients, or complete diets, is the use of regression equations based on chemical composition of ingredients. As such, we chose to compare four systems of calculating NE using proximate analysis for our major ingredients; 1) NRC 1; 2) NRC 2; 3) EvaPig software (INRA, 2008); and 4) CVB feedstuff database webapp (CVB, 2020). These NE estimates were then used to calculate CE values based on live weight ADG and carcass weight ADG. When NE was calculated using the NRC 1 or INRA (2008) equation systems, CE was improved, suggesting that each system underestimated the NE of low-energy diets used in the study herein. This similarity in response was expected as both systems of equations are based on the same work of Noblet et al. (1994), with slight modifications being made to the INRA (2008) equations based on the work of Sauvant et al. (2004). However, when NE was calculated based on the NRC 2 method, CE worsened with decreasing NE, suggesting that the DE values within the NRC (2012) database greatly overestimate the energy content of our low-energy diets. There was no difference observed when live CE was calculated based on NE values from the CVB (2020) system of equation, but carcass CE slightly, but significantly, worsened. These results would suggest that of the available equations, the CVB (2020) system of equations most closely estimates the true NE value of the reduced energy diets used in our study.

In conclusion, these results agree with previous research in that reducing NE, via high inclusion of fibrous ingredients, reduced ADG and G:F while increasing ADFI of growing finishing pigs. Additionally, reducing NE decreased HCW, backfat depth, and carcass yield, but increased carcass lean percentage. Caloric efficiency estimates (live and carcass gain basis) suggest that the NRC database overestimates NE of low energy diets, while the INRA database underestimates their NE. Meanwhile, NE values in the CVB database appear to most accurately represent these diets based on live gain but underestimate them on a carcass basis. Alternatively, calculating NE based on the Brazilian Tables appear to underestimate dietary NE of our low energy diets on a live basis, but was most accurate based on carcass growth. When using analyzed chemical composition of ingredients, and the system of equations, the CVB (2020) appears to be the most accurate of the available equations. Overall, the results of this study reinforce the importance of establishing and utilizing accurate energy values of ingredients to economically value them appropriately.

References

Asmus, M. D., J. M. DeRouchey, M. D. Tokach, S. S. Dritz, T. A. Houser, J. L. Nelssen, and R. D. Goodband. 2014. Effects of lowering dietary fiber before marketing on finishing pig growth performance, carcass characteristics, carcass fat quality, and intestinal weights. J. Anim. Sci. 92:119-128. doi:10.2527/jas2013-6679.

Black, J. L., R. G. Campbell, I. H. Williams, K. J. James, and G. T. Davis. 1986. Simulation of energy and amino acid utilization in the pig. Res. Dev. Agric. 3:121-146.

Blok, M. C. 2006. Development of a new net energy formula by CVB, using the database of INRA. Int. Sym. Proc. Net energy systems for growing and fattening pigs; Vejle, Denmark.

Blok, M. C., Brandsma, G., Bosch, G., Gerrits, W. J. J., Jansman, A. J. M., and Everts, H. 2015. A new Dutch net energy formula for feed and feedstuffs for growing and fattening pigs. CVB-Documentation report; No. 56. Wageningen UR Livestock Research. https://edepot.wur.nl/375605.

Boyd, R. D., C. E. Zier-Rush, and C. E., Fralick. 2011. Practical method for productive energy (NEm+g) estimation of soybean meal for growing pigs. J. Anim. Sci. 89(Suppl. 2):89 (Abstr.).

Brazilian Tables for Poultry and Swine. 2024. Feedstuff composition and nutritional requirements. 5th ed. H. S. Rostagno (ed), L. F. T. Albino (ed). Department of Animal Science, UFV, Viçosa, MG, Brazil.

Cemin, H. S., H. E. Williams, M. D. Tokach, S. S. Dritz, J. C. Woodworth, J. M. DeRouchey, R. D. Goodband, K. F. Coble, B.A. Carrender, and M. J. Gerhart. 2020. Estimate of the energy value of soybean meal relative to corn based on growth performance of nursery pigs. J. Anim. Sci. Biotechnol. 11:70. doi:10.1186/s40104-020-00474-x.

Coble, K. F., J. M. DeRouchey, M. D. Tokach, S. S. Dritz, R. D. Goodband, and J. C. Woodworth. 2018. Effects of withdrawing high-fiber ingredients before marketing on finishing pig growth performance, carcass characteristics, and intestinal weights. J. Anim. Sci. 96:168-180. doi:10.1093/jas/skx048.

Central Bureau Livestock Feeding (CVB). 2020. Booklet of feeding tables for pigs. CVB Foundation, Wageningen Livestock Research and Flemish Institute for Agricultural, Fisheries, and Food Research.

De la Llata, M., S. S. Dritz, M. D. Tokach, R. D. Goodband, and J. L. Nelssen. 2007. Effects of increasing lysine to calorie ratio and added fat for growing-finishing pigs reared in a commercial environment: I. Growth performance and carcass characteristics. Prof. Anim. Sci. 23:417-428. doi:10.15232/S1080-7446(15)30997-9.

de Leeuw, J. A., J. E. Bolhuis, G. Bosch, and W. J. J. Gerrits. 2008. Effects of dietary fibre on behavior and satiety in pigs. Proc. Nutr. Soc. 67:334-342. doi:10.1017/S002966510800863X.

EPA. 2024. Overview of the Renewable Fuel Standard Program. [accessed June 28, 2024]. https://www.epa.gov/renewable-fuel-standard-program/overview-renewable-fuel-standard-program.

Estrada, J. E., M. Ellis, O. F. Mendoza, and A. M. Gaines. 2017. Estimation of the productive energy content of corn germ meal based on a growth assay in wean-to-finish pigs. J. Anim. Sci. 95:(Suppl.2):95. (Abstr.). doi:10.2527/asasmw.2017.12.195.

EvaPig. 2008. Evaluation of pig feeds- equations and coefficients. INRA, AFX, Ajinomoto Eurolysine SAS.

Gahl, M. J., T. D. Crenshaw, and N. J. Benevega. 1995. Diminishing returns in weight, nitrogen, and lysine gain of pigs fed six levels of lysing from three supplemental sources. J. Anim. Sci. 73:3177-3187. doi:10.2527/1994.72123177x.

Graham, A. B., R. D. Goodband, M. D. Tokach, S. S. Dritz, J. M. DeRouchey, and S. Nitikanchana. 2014a. The effect of medium-oil dried distillers grains with solubles on growth performance, carcass traits, and nutrient digestibility in growing-finishing pigs. J. Anim. Sci. 92:604-611. doi:10.2527/jas2013-6798.

Graham, A. B., R. D. Goodband, M. D. Tokach, S. S. Dritz, J. M. DeRouchey, S. Nitikanchana, and J. J. Updike. 2014b. The effects of low-, medium-, and high-oil distillers dried grains with solubles on growth performance, nutrient digestibility, and fat quality in finishing pigs. J. Anim. Sci. 92:3610-3623. doi:10.2527/jas.2014-7678.

Hagen, C. S., B. Peterson, E. Parr, J. Estrada, G. Silva, and L. L. Greiner. 2023. The impact of floor space allowance and dietary energy level on finishing pigs, from 65 to 120 kg, on growth performance. Transl. Anim. Sci. 7:txad070. doi:10.1093/tas/txad070.

Henry, Y. 1985. Dietary factors involved in feed intake regulation in growing pigs: A review. Livest. Prod. Sci. 12:339-354. doi:10.1016/0301-6226(85)90133-2.

Just, A. 1982. The influence of ground barley straw on the net energy value of diets for growth in pigs. Livest. Prod. Sci. 9:717-729. doi:10.1016/0301-6226(82)90019-7.

Lerner, A. B., M. D. Tokach, J. M. DeRouchey, S. S. Dritz, R. D. Goodband, J. C. Woodworth, and M. Allerson. 2020a. Effects of switching from corn distillers dried grains with solubles- to corn- and soybean meal-based diets on finishing pig performance, carcass characteristics, and carcass fatty acid composition. Transl. Anim. Sci. 4:715–723. doi:10.1093/tas/txaa070.

Lerner, A. B., M. D. Tokach, J. M. DeRouchey, S. S. Dritz, R. D. Goodband, J. C. Woodworth,

C. W. Hastad, K. F. Coble, E. Arkfeld, H. C. Cartagena, and C. Vahl. 2020b. Effects of corn distillers dried grains with solubles in finishing diets on pig growth performance and carcass yield with two different marketing strategies. Transl. Anim. Sci. 4:737–749. doi:10.1093/tas/txaa071.

Marçal, D. A., C. Kiefer, M. D. Tokach, S. S. Dritz, J. C. Woodworth, R. D. Goodband, H. S. Cemin, and J. M. DeRouchey. 2019. Diet formulation method influences the response to increasing net energy in finishing pigs. Transl. Anim. Sci. 3:1349-1358. doi:10.1093/tas/txz147.

Nitikanchana, S., S. S. Dritz, M. D. Tokach, J. M. DeRouchey, R.D. Goodband, and B. J. White. 2015. Regression analysis to predict growth performance from dietary net energy in growing-finishing pigs. J. Anim. Sci. 93:2826-2839. doi:10.2527/jas2015-9005.

Nemechek, J. E., M. D. Tokach, S. S. Dritz, R. D. Goodband, J. M. DeRouchey, and J. C. Woodworth. 2015. Effects of diet form and type on growth performance, carcass yield, and iodine value of finishing pigs. J. Anim. Sci. 93:4486-4499. doi:10.2527/jas2015-9149.

Noblet, J., H. Fortune, X. S. Shi, and S. Dubois. 1994. Prediction of net energy value of feeds for growing pigs. J. Anim. Sci. 72:344-354. doi:10.2527/1994.722344x.

Noblet, J., J. van Milgen. 2004. Energy value of pig feeds: Effect of pig body weight and energy evaluation system. J. Anim. Sci. 82:(E. Suppl.):E299-E238. doi:10.2527/2004.8213_supplE229x.

Noblet, J., S. B. Wu, and M. Choct. 2022. Methodologies for energy evaluation of pig and poultry feeds: A review. Anim. Nutr. 8:185-203. doi:10.1016/j.animu.2021.06.015.

NRC. 2012. Nutrient requirements of swine: 11th ed. Natl. Acad. Press, Washington, DC.

Nyachoti, C. M., R. T. Zijlstra, C. F. M. de Lange, and J. F. Patience. 2004. Voluntary feed intake in growing-finishing pigs: A review of the main determining factors and potential approaches for accurate predictions. Can. J. Anim. Sci. 84:549-566. doi:10.414/A04-001.

Patience, J., D. Beaulieu, N. Williams, and D. Gillis. 2006. Response of growing and finishing pigs to dietary energy concentration. Conference paper, Canada, Exeter, 25th Annual Centralia Swine Research Update. (2006): II-35.

PIC. 2021. PIC Nutrition and feeding guidelines. [accessed June 28, 2024]. https://www.pic.com/wp-content/uploads/sites/3/2021/03/PIC-Nutition-Manual_English-Imperial.pdf

Salyer, J. A., J. M. DeRouchey, M. D. Tokach, S. S. Dritz, R. D. Goodband, J. L. Nelssen, and D. B. Petry. 2012. Effects of dietary wheat middlings, distillers dried grains with solubles, and choice white grease on growth performance, carcass characteristics, and carcass fat quality of finishing pigs. J. Anim. Sci. 90:2620-2630. doi:10.2527/jas2011 4472.

Sauvant, D., J. M. Perez, and G. Tran. 2004. Tables of composition and nutritional value of feed materials: Pig, poultry, sheep, goats, rabbits, horses, and fish. Wageningen Academic Publishers; Wageningen, the Netherlands:2004. INRA ed. Paris, France.

Stein, H. H., and R. A. Easter. 1996. Effects of decreasing dietary energy concentration in finishing pigs on carcass composition. J. Anim. Sci. 74(Suppl.1):65 (Abstr.)

Van Soest, P. J., J. B. Robertson, and B. A. Lewis. 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. J. Dairy Sci. 74:3583-3597. doi:10:3168/jds.S0022-0302(91)78551-2.

Zhao, Y., C. Liu, J. Niu, Z. Cui, X. Zhao, W. Li, Y. Zhang, Y. Yang, P. Gao, X. Guo, B. Li, S. W. Kim, and G. Cao. 2023. Impacts of dietary fiber level on growth performance, apparent digestibility, intestinal development, and colonic microbiota and metabolome of pigs. J. Anim. Sci. 101:1-16. doi:10.1093/jas/skad174.

Table 1.1. Analysis of corn, soybean meal, corn DDGS, and wheat middlings (as-is basis)[1]

Item, %	Ground corn	Soybean meal	Corn dried distillers grains with solubles	Wheat middlings
Dry matter	85.2	87.6	89.2	86.6
CP	7.4	46.3	30.6	18.0
Starch	61.7	1.1	1.8	13.5
Ether extract	3.1	1.8	6.0	3.6
Acid detergent fiber	2.7	4.8	11.2	12.3
Neutral detergent fiber	7.0	5.5	27.8	39.2
Ash	1.2	5.8	5.0	5.4
Total amino acids				
Alanine	0.43	1.61	1.86	0.60
Arginine	0.30	3.18	1.29	1.10
Aspartic acid	0.48	5.15	1.96	1.04
Cysteine	0.15	0.61	0.57	0.35
Glutamic acid	1.24	8.09	5.29	3.10
Glycine	0.42	2.96	1.88	0.69
Histidine	0.18	1.15	0.80	0.44
Isoleucine	0.23	1.97	1.14	0.51
Leucine	0.80	3.38	3.58	1.03
Lysine	0.34	2.77	0.94	0.65
Methionine	0.14	0.66	0.62	0.25
Phenylalanine	0.22	2.28	1.49	0.53
Proline	0.63	2.31	2.68	1.72
Serine	0.33	2.32	1.49	0.81
Threonine	0.25	1.79	1.15	0.53
Tryptophan	0.05	0.61	0.24	0.19
Tyrosine	0.01	1.29	1.03	0.29
Valine	0.32	2.02	1.42	0.72

[1] Five representative samples of each ingredient were analyzed (Midwest Laboratories, Omaha, NE, USA). Mean values were used in diet formulation.

Table 1.2. Composition of phase 1, 2, and 3 diets (as-fed basis)[1,2,3]

Dietary phase:	1		2			3		
NE reduction, %:	0	8	0	4	8	0	4	8
Item								
Ingredient, %								
Corn	64.32	31.77	69.48	52.98	36.92	74.70	58.32	41.94
Soybean meal, 46.5% CP	32.04	25.34	27.26	24.01	20.33	22.47	18.97	15.47
Wheat middlings	---	25.00	---	12.50	25.00	---	12.50	25.00
Corn DDGS	---	15.00	---	7.50	15.00	---	7.50	15.00
Monocalcium P, 21% P	0.60	---	0.45	0.23	---	0.30	0.15	---
Limestone	1.05	1.55	0.98	1.25	1.52	0.94	1.22	1.51
Sodium chloride	0.53	0.45	0.55	0.49	0.43	0.55	0.49	0.43
L-Lys-HCl	0.45	0.34	0.40	0.36	0.31	0.35	0.31	0.28
DL-Met	0.24	0.08	0.19	0.12	0.04	0.14	0.07	0.01
Thr biomass[4]	0.28	0.14	0.23	0.17	0.10	0.19	0.14	0.09
L-Trp	0.04	0.01	0.04	0.03	0.02	0.04	0.03	0.02
L-Val	0.11	---	0.08	0.04	---	0.06	0.03	---
Vitamin premix with phytase[5]	0.20	0.20	0.20	0.20	0.20	0.15	0.15	0.15
Trace mineral premix	0.15	0.15	0.15	0.15	0.15	0.13	0.13	0.13
Total	100	100	100	100	100	100	100	100
Calculated analysis[1]								
SID AA, %								
Lys, %	1.27	1.17	1.12	1.08	1.03	0.97	0.93	0.89
Ile:Lys	58	66	58	63	67	59	63	68
Leu:Lys	113	142	118	133	150	125	142	160
Met:Lys	38	32	37	34	31	36	33	30
Met and Cys:Lys	59	59	59	59	59	59	59	60
Thr:Lys	66	66	66	66	66	66	67	68
Trp:Lys	20.0	20.1	20.3	20.5	20.7	20.3	20.7	21.0
Val:Lys	70	75	70	73	77	70	75	80
His:Lys	35	43	35	40	45	36	41	47
NE, kcal/kg, using ingredient databases								
NRC	2,426	2,226	2,458	2,355	2,256	2,491	2,388	2,285
INRA	2,366	1,999	2,401	2,215	2,032	2,438	2,251	2,065
CVB	2,372	2,102	2,408	2,271	2,136	2,445	2,307	2,170
Brazilian Tables	2,391	2,093	2,424	2,272	2,124	2,458	2,306	2,155
NE, kcal/kg, with analyzed ingredient values								
NRC 1[6]	2,478	2,044	2,505	2,285	2,068	2,533	2,313	2,092
NRC 2[7]	2,432	2,237	2,463	2,363	2,266	2,495	2,395	2,295
INRA[8]	2,399	2,019	2,429	2,237	2,047	2,460	2,267	2,074
CVB[9]	2,335	2,073	2,367	2,234	2,103	2,400	2,267	2,133
SID Lys:NE, g/Mcal[10]	5.22	5.23	4.55	4.57	4.54	3.89	3.88	3.88
CP, %	20.5	23.1	18.5	19.9	21.0	16.5	17.8	19.1
STTD P:NE, g/Mcal[10]	1.62	1.62	1.43	1.43	1.43	1.25	1.25	1.25
STTD P, %	0.40	0.43	0.36	0.39	0.42	0.32	0.37	0.41
Ca, %	0.70	0.79	0.62	0.69	0.76	0.55	0.64	0.73

Total Ca:P	1.32	1.32	1.32	1.32	1.32	1.32	1.32	1.32
NDF, %	6.3	16.9	6.4	11.7	17.0	6.5	11.8	17.1
Crude Fat, %	2.6	3.6	2.6	3.1	3.6	2.7	3.2	3.7

---

[1] Calculated analysis is based off chemical analysis of corn, soybean meal, wheat middlings, and corn DDGS, and nutrient profiles for ingredients listed in the NRC for all other ingredients.

[2] Zero and 8% reduced NE diets were blended to achieve treatment diets at 2, 4, and 6% NE reductions in phase 1. Within phases 2 and 3, 0 and 4% or 4 and 8% reduced NE diets were blended to achieve 2 and 6% reduced NE treatment diets, respectively.

[3] Phases 1, 2, and 3 were fed from approximately 23 to 40 kg, 40 to 60 kg, and 60 to 80 kg, respectively.

[4] THR Pro; CJ America-Bio, Downers Grove, IL.

[5] Axtra PHY (Dupont, Wilmington, DE) provided 429 phytase units (FTU/kg) for an estimated release of 0.12% STTD P.

[6] NE kcal/kg calculated as an average of Eq. 1-7 and 1-8 as explained in the NRC (2012) using values derived from proximate analysis. Eq. 1-7; NE = (0.726 × ME) + (1.33 × EE) + (0.39 × Starch) – (0.62 × CP) – (0.83 × ADF); Eq. 1-8; NE = (0.700 × DE) + (1.61 × EE) + (0.48 × Starch) – (0.91 × CP) – (0.87 × ADF); with DE and ME calculated using Eq. 1-2 through 1-6.

[7] NE kcal/kg = (0.700 × DE) + (1.61 × EE) + (0.48 × Starch) – (0.91 × CP) – (0.87 × ADF); DE values derived from NRC (2012) ingredient database.

[8] NE kcal/kg = $\mathrm{NE/ME_{ref}} + [(5.5 \times (\mathrm{EE_{new}} - \mathrm{EE_{ref}}) + 1.5 \times (\mathrm{Starch_{new}} - \mathrm{Starch_{ref}}) - 2.8 \times (\mathrm{CP_{new}} - \mathrm{CP_{ref}})] / \mathrm{ME_{new}}$. Whereas; ref = reference values within the EvaPig software; and new = values derived from proximate analysis.

[9] NE kcal/kg = [(11.7 × CP) + (35.74 × EE) + [14.14 × (Starch + Glucose oligosaccharides + 0.90 × fermented sugars)] + (9.74 × fermented degradable carbohydrates) + (10.61 × acetic acid) + (14.62 × propionic acid) + (19.52 × butyric acid) + (20.75 × ethanol) + (12.02 × lactic acid) + (13.83 × glycerol)] × 0.23900574 × 0.45359237.

[10] Net energy estimates derived from the NRC 2 equation were used to calculate SID Lys:NE and STTD P:NE ratios.

Table 1.3. Composition of phase 4 and 5 diets (as-fed basis)[1,2,3]

Dietary phase:	4			5		
NE reduction, %:	0	4	8	0	4	8
Ingredient, %						
Corn	78.52	62.01	45.94	81.15	64.96	48.77
Soybean meal, 46.5% CP	18.99	15.50	11.58	16.79	12.80	8.82
Wheat middlings	---	12.50	25.00	---	12.50	25.00
Corn DDGS	---	7.50	15.00	---	7.50	15.00
Monocalcium P, 21% P	0.20	0.10	---	---	---	---
Limestone	0.91	1.21	1.51	0.84	1.16	1.49
Sodium chloride	0.55	0.50	0.45	0.55	0.50	0.45
L-Lys-HCl	0.30	0.28	0.25	0.25	0.24	0.23
DL-Met	0.10	0.05	---	0.07	0.03	---
Thr biomass[4]	0.15	0.10	0.04	0.12	0.07	0.02
L-Trp	0.03	0.02	0.01	0.02	0.01	0.01
L-Val	0.03	0.01	---	---	---	---
Vitamin premix with phytase[5]	0.13	0.13	0.13	0.13	0.13	0.13
Trace mineral premix	0.10	0.10	0.10	0.10	0.10	0.10
Total	100	100	100	100	100	100
Calculated analysis[1]						
SID AA, %						
Lys, %	0.85	0.82	0.78	0.76	0.73	0.70
Ile:Lys	60	65	69	62	66	70
Leu:Lys	133	151	171	143	161	181
Met:Lys	35	33	31	33	33	33
Met and Cys:Lys	59	61	64	59	63	67
Thr:Lys	66	66	66	66	66	66
Trp:Lys	20.4	20.3	20.1	20.0	20.1	20.2
Val:Lys	70	76	83	70	78	86
His:Lys	38	43	49	40	45	51
NE, kcal/kg, ingredient databases						
NRC	2,515	2,410	2,308	2,534	2,429	2,325
INRA	2,464	2,276	2,091	2,484	2,297	2,109
CVB	2,472	2,332	2,196	2,492	2,353	2,215
Brazilian Tables	2,482	2,329	2,179	2,501	2,349	2,196
NE, kcal/kg, analyzed ingredient values						
NRC 1[6]	2,553	2,331	2,111	2,569	2,347	2,124
NRC 2[7]	2,518	2,417	2,317	2,537	2,435	2,334
INRA[8]	2,482	2,288	2,096	2,500	2,305	2,111
CVB[9]	2,424	2,289	2,156	2,442	2,308	2,173
SID Lys:NE, g/Mcal[10]	3.38	3.39	3.37	3.00	3.00	3.00
CP, %	15.1	16.4	17.5	14.1	15.3	16.4
STTD P:NE, g/Mcal[10]	1.10	1.10	1.10	0.99	0.99	0.99
STTD P, %	0.30	0.35	0.40	0.25	0.32	0.39
Ca, %	0.51	0.61	0.71	0.44	0.56	0.69

Total Ca:P	1.32	1.32	1.32	1.32	1.32	1.32
NDF, %	6.5	11.8	17.2	6.6	11.9	17.2
Crude Fat, %	2.8	3.3	3.8	2.8	3.3	3.8

---

[1] Calculated analysis is based off chemical analysis of corn, soybean meal, wheat middlings, and corn DDGS, and nutrient profiles for ingredients listed in the NRC for all other ingredients.

[2] Zero and 4% or 4 and 8% reduced NE diets were blended to achieve treatment diets at 2 and 6% reduced NE, respectively.

[3] Phases 4 and 5 were fed from approximately 80 to 104 kg and 104 to 133 kg, respectively.

[4] THR Pro; CJ America-Bio, Downers Grove, IL.

[5] Axtra PHY (Dupont, Wilmington, DE) provided 429 phytase units (FTU/kg) for an estimated release of 0.12% STTD P.

[6] NE kcal/kg calculated as an average of Eq. 1-7 and 1-8 as explained in the NRC (2012) using values derived from proximate analysis. Eq. 1-7; NE = (0.726 × ME) + (1.33 × EE) + (0.39 × Starch) – (0.62 × CP) – (0.83 × ADF); Eq. 1-8; NE = (0.700 × DE) + (1.61 × EE) + (0.48 × Starch) – (0.91 × CP) – (0.87 × ADF); with DE and ME calculated using Eq. 1-2 through 1-6.

[7] NE kcal/kg = (0.700 × DE) + (1.61 × EE) + (0.48 × Starch) – (0.91 × CP) – (0.87 × ADF); DE values derived from NRC (2012) ingredient database.

[8] NE kcal/kg = $NE/ME_{ref} + [(5.5 \times (EE_{new} - EE_{ref}) + 1.5 \times (Starch_{new} - Starch_{ref}) - 2.8 \times (CP_{new} - CP_{ref})] / ME_{new}$. Whereas; ref = reference values within the EvaPig software; and new = values derived from proximate analysis.

[9] NE kcal/kg = [(11.7 × CP) + (35.74 × EE) + [14.14 × (Starch + Glucose oligosaccharides + 0.90 × fermented sugars)] + (9.74 × fermented degradable carbohydrates) + (10.61 × acetic acid) + (14.62 × propionic acid) + (19.52 × butyric acid) + (20.75 × ethanol) + (12.02 × lactic acid) + (13.83 × glycerol)] × 0.23900574 × 0.45359237.

[10] Net energy estimates derived from the NRC 2 equation were used to calculate SID Lys:NE and STTD P:NE ratios.

Table 1.4 Chemical analysis of diets (as-fed basis)[1,2]

Dietary Phase:	1		2			3			4			5		
NE Reduction, %:	0	8	0	4	8	0	4	8	0	4	8	0	4	8
Chemical Analysis, %														
Dry Matter	86.8	87.1	86.7	87.2	87.3	86.2	86.5	86.7	58.7	86.4	87.4	86.2	86.6	86.9
CP	20.1	22.2	18.6	23.1	26.7	16.3	18.3	20.0	14.4	18.1	18.6	13.8	15.6	16.0
Starch	40.7	25.0	42.4	31.0	19.5	48.4	38.4	29.0	48.5	35.5	35.3	54.8	43.1	34.0
Ether extract	2.5	3.1	2.6	3.1	3.3	2.8	3.1	3.2	2.9	3.2	3.7	2.9	3.5	3.9
Acid detergent fiber	3.2	6.4	2.6	4.3	6.5	2.1	4.3	5.6	2.6	5.1	5.9	2.4	4.8	6.2
Neutral detergent fiber	6.3	17.9	6.5	11.5	16.2	7.6	11.7	16.0	7.4	14.8	15.4	6.9	12.9	17.6
Ash	5.0	6.2	4.4	5.4	7.1	3.9	4.5	5.0	2.9	4.5	4.4	3.0	3.8	4.2

[1] Diet samples were taken from 15 feeders approximately 3 d after the beginning of the trial and stored at -20°C. Values are reported on a total analyzed basis.

[2] Composite samples were submitted to Midwest Laboratories (Omaha, NE, USA) for chemical analysis

Table 1.5. Effects of reducing net energy on finishing pig performance[1]

	NE reduction, %						*P* =	
	0	2	4	6	8	SEM	Linear	Quadratic
Body weight, kg								
d 0	23.5	23.3	23.3	23.3	23.3	0.23	0.227	0.120
d 22	40.7	40.3	40.0	39.5	38.4	0.34	< 0.001	0.008
d 43	60.6	60.1	59.3	58.3	56.7	0.40	< 0.001	0.013
d 66	82.5	82.0	81.1	79.5	77.9	0.49	< 0.001	0.058
d 90	107.0	105.6	104.8	102.8	100.8	0.57	< 0.001	0.153
d 125	140.4	137.5	137.1	134.9	131.2	1.06	< 0.001	0.193
Marketing weights, kg								
d 99	125.0	125.3	120.7	120.4	116.9	1.19	< 0.001	0.462
d 111	135.7	131.7	132.1	130.0	126.6	1.16	< 0.001	0.754
Overall average[2]	137.4	134.4	134.0	131.8	128.3	0.82	< 0.001	0.296
d 0 to 22 (Phase 1)								
ADG, kg	0.78	0.77	0.76	0.73	0.68	0.007	< 0.001	< 0.001
ADFI, kg	1.28	1.27	1.45	1.23	1.18	0.015	< 0.001	0.052
G:F, g/kg	609	611	605	599	577	4.2	< 0.001	< 0.001
SID Lys intake, g/d	16.21	15.77	15.22	14.65	13.80	0.177	< 0.001	0.077
SID Lys intake, g/kg gain	20.88	20.40	20.16	19.96	20.29	0.140	< 0.001	< 0.001
NE Intake, kcal/d	3,105	3,019	2,912	2,802	2,639	33.9	< 0.001	0.078
d 22 to 43 (Phase 2)								
ADG, kg	0.95	0.94	0.91	0.89	0.87	0.008	< 0.001	0.708
ADFI, kg	1.68	1.77	1.83	1.87	1.95	0.020	< 0.001	0.538
G:F, g/kg	567	530	500	476	448	4.3	< 0.001	0.118
SID Lys intake, g/d	18.80	19.52	19.72	19.69	20.05	0.220	< 0.001	0.184
SID Lys intake, g/kg gain	19.79	20.75	21.62	22.16	22.98	0.171	< 0.001	0.317
NE Intake, kcal/d	4,135	4,281	4,316	4,320	4,410	48.2	< 0.001	0.367
d 43 to 66 (Phase 3)								
ADG, kg	0.95	0.95	0.94	0.92	0.91	0.011	0.001	0.700
ADFI, kg	2.28	2.31	2.33	2.32	2.35	0.024	0.015	0.621
G:F, g/kg	419	409	404	397	389	3.4	< 0.001	0.844
SID Lys intake, g/d	22.07	21.96	21.68	21.08	20.92	0.222	< 0.001	0.598
SID Lys intake, g/kg gain	23.19	23.24	23.06	22.93	22.91	0.198	0.054	0.887
NE Intake, kcal/d	5,679	5,652	5,583	5,433	5,396	57.1	< 0.001	0.599
d 66 to 90 (Phase 4)								
ADG, kg	1.02	0.98	0.99	0.97	0.95	0.011	< 0.001	0.798
ADFI, kg	2.55	2.55	2.63	2.61	2.65	0.026	< 0.001	0.990
G:F, g/kg	398	386	376	371	360	3.1	< 0.001	0.636
SID Lys intake, g/d	21.69	21.28	21.53	20.84	20.66	0.211	< 0.001	0.489
SID Lys intake, g/kg gain	21.39	21.67	21.84	21.56	21.71	0.178	0.312	0.271
NE Intake, kcal/d	6,427	6,288	6,347	6,165	6,139	62.3	< 0.001	0.940
d 90 to 125 (Phase 5)								
ADG, kg	1.02	0.98	0.98	0.97	0.92	0.014	< 0.001	0.581
ADFI, kg	2.99	2.99	3.10	3.08	3.10	0.024	< 0.001	0.320

G:F, g/kg	339	327	315	316	298	3.7	< 0.001	0.945
SID Lys intake, g/d	22.73	22.26	22.61	22.01	21.71	0.175	< 0.001	0.276
SID Lys intake, g/kg gain	22.47	22.80	23.18	22.71	23.55	0.260	0.006	0.843
NE Intake, kcal/d	7,587	7,426	7,542	7,341	7,236	58.2	< 0.001	0.275
d 0 to 125 (Overall)								
ADG, kg	0.95	0.93	0.92	0.90	0.87	0.005	< 0.001	0.121
ADFI, kg	2.21	2.23	2.28	2.27	2.30	0.016	< 0.001	0.346
G:F, g/kg	429	416	403	397	380	1.8	< 0.001	0.749
Carcass ADG, kg[3]	0.69	0.68	0.67	0.65	0.63	0.004	< 0.001	0.185
Carcass G:F, g/kg[4]	314	304	293	287	273	1.4	< 0.001	0.827
SID Lys intake, g/d	20.47	20.30	20.31	19.80	19.56	0.140	< 0.001	0.148
SID Lys intake, g/kg gain	21.62	21.84	22.04	21.91	22.34	0.098	< 0.001	0.822
NE Intake, kcal/d	5,528	5,468	5,481	5,343	5,294	37.7	< 0.001	0.298
Removals, %	1.56	1.30	1.83	2.58	3.37	0.918	0.073	0.355
Mortality, %	4.42	3.38	3.39	3.09	2.33	1.047	0.131	0.908
Total, %	5.97	4.68	5.22	5.67	5.70	1.208	0.877	0.551

---

[1] A total of 1,927 pigs (initially 23.3 ± 0.23 kg) were used in a growth performance study with 23 to 26 pigs per pen and 15 replicates per treatment.

[2] Weighted average of weights from all marketing events. Between 0 to 5 pigs/pen were marketed on d 99, 3 or 4 pigs per pen were marketed on d 111, with the remaining pigs being marketed on d 125.

[3] Carcass ADG calculated as: Carcass yield × overall live ADG.

[4] Carcass G:F calculated as: overall ADFI ÷ Carcass ADG.

Table 1.6. Effects of reducing net energy on carcass characteristics of finishing pigs[1]

	NE reduction, %						*P* =	
	0	2	4	6	8	SEM	Linear	Quadratic
d 99								
Count, n	49	56	45	53	51			
HCW, kg	91.7	91.3	87.6	87.7	85.1	0.84	< 0.001	0.894
Carcass yield, %	73.2	73.2	72.8	73.0	72.2	0.25	0.001	0.146
Backfat depth, cm	1.45	1.39	1.41	1.29	1.27	0.040	< 0.001	0.612
Loin depth, cm	6.64	6.62	6.49	6.51	6.62	0.073	0.553	0.123
Lean, %	58.1	58.3	58.1	58.8	59.0	0.27	0.006	0.355
d 111								
Count, n	50	51	49	53	53			
HCW, kg	100.0	96.9	96.9	94.6	91.7	0.97	< 0.001	0.588
Carcass yield, %	73.1	72.9	72.6	72.4	72.0	0.24	< 0.001	0.797
Backfat depth, cm	1.55	1.46	1.44	1.39	1.31	0.045	< 0.001	0.961
Loin depth, cm	6.61	6.54	6.78	6.63	6.62	0.093	0.990	0.182
Lean, %	57.4	57.8	57.9	58.2	58.8	0.32	0.003	0.569
d 125								
Count, n	228	226	213	228	196			
HCW, kg	103.7	100.7	100.3	98.1	95.4	0.72	< 0.001	0.584
Carcass yield, %	73.1	72.9	72.5	72.2	72.2	0.19	< 0.001	0.198
Backfat depth, cm	1.60	1.59	1.53	1.45	1.43	0.027	< 0.001	0.892
Loin depth, cm	6.86	6.93	6.93	7.00	6.91	0.048	0.220	0.157
Lean, %	57.3	57.5	57.9	58.4	58.4	0.18	< 0.001	0.708
Overall								
Count, n	327	333	307	334	300			
HCW, kg	101.3	98.5	98.0	95.9	93.0	0.62	< 0.001	0.412
Carcass yield, %	73.2	73.0	72.6	72.3	72.1	0.15	< 0.001	0.676
Backfat depth, cm	1.56	1.53	1.49	1.42	1.40	0.021	< 0.001	0.823
Loin depth, cm	6.79	6.83	6.79	6.85	6.81	0.037	0.612	0.746
Lean, %	57.5	57.7	57.9	58.4	58.5	0.14	< 0.001	0.943

[1] A total of 1,927 pigs (initially 23.3 ± 0.23 kg) were used in a 125-d growth performance study with 23 to 26 pigs per pen and 15 replicates per treatment.

[2] Weighted average from all marketing events. Between 0 to 5 pigs/pen were marketed on d 99, 3 or 4 pigs were marketed on d 111, with the remaining pigs marketed on d 125.

Table 1.7. Effects of reducing net energy on caloric efficiency of finishing pigs based on ingredient databases and analyzed ingredient NE values[1]

	NE reduction, %						*P* =	
	0	2	4	6	8	SEM	Linear	Quadratic
Ingredient databases								
d 0 to 125 (overall)								
CE, kcal/kg gain[2]								
NRC[3]	5,833	5,884	5,950	5,907	6,043	25.9	< 0.001	0.495
INRA[4]	5,710	5,655	5,612	5,459	5,465	24.5	< 0.001	0.908
CVB[5]	5,727	5,731	5,752	5,662	5,741	25.1	0.572	0.664
Brazilian Tables[6]	5,756	5,744	5,747	5,641	5,699	25.1	0.004	0.741
CE, kcal/kg carcass gain[7]								
NRC	7,954	8,051	8,193	8,173	8,402	38.6	< 0.001	0.470
INRA	7,785	7,740	7,727	7,553	7,598	36.5	< 0.001	0.901
CVB	7,809	7,845	7,919	7,834	7,981	37.3	0.004	0.633
Brazilian Tables	7,848	7,862	7,913	7,804	7,925	37.3	0.393	0.699
Analyzed Ingredient Values								
d 0 to 125 (overall)								
CE, kcal/kg gain[2]								
NRC 1[8]	5,928	5,839	5,759	5,566	5,529	25.2	< 0.001	0.904
NRC 2[9]	5,843	5,895	5,967	5,929	6,067	26.0	< 0.001	0.506
INRA[10]	5,760	5,698	5,649	5,488	5,485	24.7	< 0.001	0.971
CVB[11]	5,620	5,626	5,648	5,563	5,641	24.6	0.741	0.673
CE, kcal/kg carcass gain[7]								
NRC 1	8,083	7,992	7,929	7,699	7,688	37.5	< 0.001	0.930
NRC 2	7,966	8,069	8,216	8,202	8,437	38.7	< 0.001	0.459
INRA	7,853	7,799	7,777	7,592	7,626	36.8	< 0.001	0.939
CVB	7,663	7,701	7,776	7,695	7,844	36.7	0.002	0.629

[1] A total of 1,927 pigs (initially 23.3 ± 0.23 kg) were used in a 125-d growth performance study with 23 to 26 pigs per pen and 15 replicates per treatment.

[2] Caloric efficiency = F/G × dietary NE (kcal/kg).

[3] NE is based off nutrient profiles for ingredients listed in the NRC (2012).

[4] NE is based off nutrient profiles for ingredients listed in EvaPig (2008).

[5] NE is based off nutrient profiles for ingredients listed in the CVB (2020).

[6] NE is based off nutrient profiles for ingredients listed in the Brazilian Tables for Poultry and Swine (2024).

[7] Caloric efficiency calculated as: Carcass F/G × dietary NE (kcal/kg).

[8] NE is based on equations 1-1 through 1-8 listed in the NRC (2012) using chemical analysis of ingredients.

[9] NE is based on equation 1-8 listed in the NRC (2012) using DE values derived from NRC (2012) ingredient database.

[10] NE is based on equations in the EvaPig software (2008) using chemical analysis of ingredients

[11] NE is based on equations in the CVB software (2020) using chemical analysis of ingredients.

Chapter 2 - Effects of standardized ileal digestible threonine to lysine ratio on growth performance of nursery, growing, and finishing pigs

Abstract

The objective of these experiments was to evaluate the effect of standardized ileal digestible (SID) Thr:Lys ratio on growth performance of late nursery, growing, and finishing pigs. Four experiments were conducted using corn-soybean meal-based diets with pigs allotted to 5 or 6 treatments in randomized complete block designs. In Exp. 1, 987 late nursery pigs (initially 11.8 ± 0.32 kg) were used with 22 to 27 pigs per pen, 8 replications per treatment, and 5 SID Thr:Lys ratios from 53 to 68% of Lys. Increasing SID Thr:Lys ratio increased (linear, $P \leq 0.005$) ADG and final BW and decreased then increased (quadratic, $P < 0.001$) ADFI therefore increasing then decreasing (quadratic, $P < 0.001$) G:F. In Exp. 2, 875 pigs (initially 43.4 ± 0.58 kg) were used with 21 to 27 pigs per pen, 7 replications per treatment, and 5 SID Thr:Lys ratios from 53 to 68% of Lys. Increasing SID Thr:Lys ratio increased (linear, $P \leq 0.037$) ADG, final BW, and G:F. Dose-response models developed using the data from Exp. 1 and 2 predicted a requirement estimate for ADG beyond the highest dose tested (68% SID Thr:Lys ratio), which led us to test a wider range of SID Thr:Lys ratios in Exp. 3 and 4. In Exp. 3, 684 pigs (initially 37.4 ± 1.36 kg) were used with 9 or 10 pigs per pen, 12 replications per treatment, and 6 SID Thr:Lys ratios from 53 to 78% of Lys. Increasing SID Thr:Lys ratio increased then plateaued (quadratic, $P \leq 0.047$) final BW, ADG, and G:F and tended (quadratic, $P = 0.093$) to decrease then increase blood urea N (BUN). In Exp. 4, 662 pigs (initially 96.2 ± 1.04 kg) were used with 8 to 10 pigs per pen, 11 or 12 replications per treatment, and 6 SID Thr:Lys ratios from 53 to 78%

of Lys. Increasing SID Thr:Lys ratio tended to increase then decrease (quadratic, $P \leq 0.063$) final BW, ADG, and G:F, with the greatest numeric response observed between 63 and 68% SID Thr:Lys ratio. Data from Exp. 3 and 4 were combined and used to fit dose response curves for ADG, G:F, and BUN. A quadratic polynomial (QP) model suggested that ADG was maximized at 68.6% SID Thr:Lys, while a similar fitting broken-line linear (BLL) model suggested no further improvement in ADG beyond 61.1% SID Thr:Lys. A BLL model suggested no further improvement in G:F beyond 59.2% SID Thr:Lys. A QP model suggested that BUN was minimized at 69.2% SID Thr:Lys. These data suggest that SID Thr:Lys requirements are similar for pigs from 37 to 70 and 96 to 120 kg.

Key Words: amino acid, grow-finish pig, lysine, threonine, requirement

Introduction

Threonine is an essential AA, which has been categorized as the first limiting AA for maintenance and development of intestinal tissue (Wang and Fuller, 1989). This is primarily due to the substantial use of Thr by the portal drained viscera to produce proteins, such as mucins, that make up most of the mucous membrane, thus supporting gut integrity and immune function (Le Floc’h and Sève 2005; Schaart et al., 2005; Jayaraman et al., 2015). Additionally, the surface area and absolute volume of the gastrointestinal tract (GIT) increases dramatically with increasing BW (Elefson et al., 2021). As a result, mucin production should increase at a corresponding rate, thus suggesting an increase in the pigs’ Thr requirement to support both intestinal maintenance and growth performance. The NRC (2012) requirement estimate suggests that the dietary standardized ileal digestible (SID) Thr:Lys ratio should increase from 59% to

65% for pigs from 11 to 135 kg BW. However, subsequent research has observed a wide range of requirement estimates for SID Thr:Lys throughout the growing-finishing period. Studies conducted since 2012 have suggested SID Thr:Lys requirement estimates to maximize ADG and G:F ranging from 61% to 71%, with little correlation to increasing BW (Zhang et al. 2013; Jayaraman et al. 2015; Remus et al. 2019). While there are a multitude of potential reasons for this variation, some include differences in environmental conditions, genetic potential for lean growth, and health status. Genetic improvement has resulted in increased protein accretion and growth performance rates, thus periodic reassessment of AA requirements is essential to allow pigs to reach their genetic potential. Therefore, the objective of these experiments was to evaluate the effect of varying SID Thr:Lys ratios on growth performance of late nursery, growing, and finishing pigs.

Materials and Methods

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocols used in these experiments. Exp. 1 and 2 were conducted in a commercial research facility located in south-central Minnesota (SVC Research, St. Peter, MN). The barn had slatted concrete flooring, deep pits for manure storage, and was naturally ventilated. Pens (3 × 5.5 m) contained a 3-hole stainless steel dry self-feeder (Thorp Equipment, Thorp, WI) and a 1-cup waterer to provide *ad libitum* access to feed and water. All treatment diets in Exp. 1 and 2 were manufactured at the United Farmers Cooperative Feed Mill (Klossner, MN). Experiments 3 and 4 were conducted at the Kansas State University Swine Teaching and Research Center in Manhattan, KS. The facilities were totally enclosed and environmentally regulated. Each pen was equipped with a 2-hole dry, single-sided feeder (Farmweld, Teutopolis, IL) and a 1-cup waterer to provide *ad libitum* access to feed and water. Pens were located over a completely slatted concrete floor with a 1.21-m pit underneath for manure storage. Complete diets were manufactured at the O.H. Kruse Feed Technology Innovation Center (Manhattan, KS). In Exp. 1 and 2, dietary treatments contained SID Thr:Lys ratios of 53, 58, 62, 65, and 68%. Diets containing 53 and 68% SID Thr:Lys were blended to create the intermediate treatment diets (Table 2.1). In Exp. 3 and 4, dietary treatments contained SID Thr:Lys ratios of 53, 58, 63, 68, 73, and 78%. The 53 and 78% SID Thr:Lys diets were blended to create the intermediate dietary treatments (Table 2.1). For all experiments, daily feed additions to each pen were accomplished using a robotic feeding system (FeedPro, Feedlogic Corp., Wilmar, MN) able to record feed amounts for individual pens. All experimental diets were corn-soybean meal-based. Dietary nutrient composition and SID AA coefficients were derived from NRC (2012). Figure 2.1 summarized the weight range of pigs, range of SID Thr:Lys ratio tested, genetic background of pigs, and location of each experiment.

In each experiment, barrows and gilts were penned together with gender accounted for within pen. For all experiments, Thr was estimated to be the first-limiting AA, with Lys formulated to be approximately 10% below requirement estimates (PIC, 2021) in Exp. 1 and 2 and approximately 10% below the requirement estimates for pigs raised in this facility (Royall et al., 2022) in Exp. 3 and 4. All other AA ratios were maintained above requirement estimates in each tria (PIC 2021). Between Exp. 1 and 2 and Exp. 3 and 4, all pens of pigs were fed a common diet for 23 and 28 d, respectively. Pens were then randomized to dietary treatment for the later experimental weight range.

Experiment 1 (12 to 24 kg BW)

A total of 987 pigs (PIC 337 × 1050; initially 11.8 ± 0.32 kg) were used in a 21-d study with 22 to 27 pigs per pen. Pens of pigs were blocked by BW and location and randomly assigned to 1 or 5 dietary treatments in a randomized complete block design (RCBD) with 8 replications per treatment. Following the conclusion of Exp. 1, all pigs were placed on a common diet for 23 days and then randomized to dietary treatment for Exp. 2.

Experiment 2 (43 to 70 kg BW)

A total of 875 pigs (PIC 337 × 1050; initially 43.4 ± 0.58 kg) were used in a 28-d study with 21 to 27 pigs per pen. Pens of pigs were blocked by BW and location and randomly assigned to 1 or 5 dietary treatments in a RCBD with 7 replications per treatment.

Experiment 3 (37 to 70 kg BW)

Two groups of pigs were used in studies lasting 35 and 28 d, respectively, for a total of 684 pigs (DNA 600 × 241; initially 37.4 ± 1.36). There were 9 or 10 mixed gender pigs per pen. Pens of pigs were blocked by BW and randomly allotted to 1 of 6 dietary treatments in a RCBD with 12 replications per treatment. Ten mL of blood was collected from the jugular vein of 3 pigs per pen (2 barrows and 1 gilt) using a Monoject blood collection tube (Covidien, Minneapolis, MN). Blood was collected after a 12-h fasting period on d 14. Whole blood was centrifuged, and serum was collected and stored at -20°C until analysis. Serum was analyzed for urea N concentration using a Urea Nitrogen Colorimetric Detection Kit (Arbor Assays, Ann Arbor, MI). Following the conclusion of Exp. 3, all pigs were placed on a common diet for 23 days and then randomized to dietary treatment for Exp. 4.

Experiment 4 (96 to 120 kg)

Two groups of pigs were used in 28 d studies, for a total of 662 pigs (DNA 600 × 241; initially 96.2 ± 1.04 kg). There were 8 to 10 mixed gender pigs per pen. Pens of pigs were blocked by BW and randomly allotted to 1 of 6 dietary treatments in a RCBD with 11 or 12 replications per treatment. Similar blood collection and analysis procedures as in Exp. 3 were conducted, with the exception that blood was collected on d 13 and 14 in groups 1 and 2, respectively.

Chemical Analysis

The diets that were used for blending in Exp. 1 and 2 and all diets in Exp. 3 and 4 were analyzed for AA profile (Table 2.2). In all experiments, dietary samples were taken from each feeder approximately 3 d after the beginning of each trial. Diet samples were stored at -20°C until they were homogenized, subsampled and submitted for AA analysis (method 994.12; AOAC International, 2012) conducted by Ajinomoto Animal Nutrition North America, Inc (Eddyville, IA) in Exp. 1, 2, and 3, and the University of Missouri-Columbia Agricultural Experiment Station Chemical Laboratories (Columbia, MO) in Exp. 4. Results of laboratory analysis indicated total nutrient profiles were consistent with expected formulated values (Table 2.2).

Statistical analysis

Data were analyzed as a randomized complete block design for a one-way ANOVA using the GLIMMIX procedure of SAS (v. 9.4, SAS Institute, Inc., Cary, NC) within each experiment. Pen was considered the experimental unit, pen average BW as a blocking factor, and treatment as the fixed effect in the statistical model. Linear and quadratic contrast coefficients were created with each experiment. Results were considered significant with $P \leq 0.05$ and marginally significant with $P \leq 0.10$. For Exp. 1 and 2, dose response curves were evaluated using quadratic polynomial (QP), broken-line linear (BLL), and broken-line quadratic (BLQ) models using the NLMIXED procedure within SAS. The best-fitting model was selected using the Bayesian Information Criterion (BIC) with improved model fits accepted when BIC decreased at least 2.0.

Data from Exp. 3 and 4 were combined and used to fit dose response curves for ADG, G:F, and BUN as a function of SID Thr:Lys ratio. Dose response curves were evaluated using quadratic polynomial (QP), broken-line linear (BLL), and broken-line quadratic (BLQ) models using the NLMIXED procedure within SAS. The best-fitting model was selected using the Bayesian Information Criterion (BIC) with improved model fits accepted when BIC decreased at least 2.0. In all dose-response models, the linear predictor included SID Thr:Lys ratio as an explanatory variable and block nested within experiment as a random effect. In addition, linear and quadratic terms for SID Thr:Lys ratio and their interaction with experiment were tested prior to fitting dose response models. There was no evidence of an interaction between SID Thr:Lys ratio and experiment and the interactive terms were eliminated from the models.

Results

Experiment 1 (11- to 24- kg PIC 337 × 1050 pigs)

Increasing SID Thr:Lys ratio increased (linear, $P < 0.005$) ADG and final BW (Table 3). Average daily feed intake decreased then increased (quadratic, $P < 0.001$) and G:F increased then decreased (quadratic, $P < 0.001$) as SID Thr:Lys ratio increased. A QP model predicted that ADG was maximized at levels greater than the highest SID Thr:Lys ratio tested (68% SID Thr:Lys), while a QP model suggested that G:F was maximized at 61.8% SID Thr:Lys (Appendix Figures A.1 and A. 2).

Experiment 2 (43- to 70-kg PIC 337 × 1050 pigs)

Increasing SID Thr:Lys increased (linear, $P \leq 0.037$) ADG, final BW, and G:F (Table 4). Quadratic polynomial models suggested that both ADG and G:F ratio were maximized at greater than 68% SID Thr:Lys. Similarly fitting BLL models predicted no further improvement in ADG and G:F beyond 67 and 65% SID Thr:Lys, respectively (Appendix Figures A.3 and A.4).

Experiment 3 (37- to 70-kg DNA 600 × 241 pigs)

Increasing SID Thr:Lys ratio increased (quadratic, $P \leq 0.025$) ADG and final BW up to 68% SID Thr:Lys ratio with no improvement thereafter (Table 5): however, ADFI was not affected ($P > 0.10$). As a result, increasing SID Thr:Lys ratio improved (quadratic, $P = 0.047$) G:F, with the greatest improvement at 58% SID Thr:Lys ratio and incremental improvements thereafter. Blood urea N tended (quadratic, $P = 0.093$) to decrease then increase with increasing SID Thr:Lys ratio.

Experiment 4 (96- to 120-kg 600 × 241 pigs)

Average daily gain and final BW increased (linear, $P = 0.035$ and quadratic, $P = 0.061$, respectively) with increasing SID Thr:Lys ratio with the greatest ADG at 68% SID Thr:Lys ratio. Increasing SID Thr:Lys ratio tended to increase (quadratic, $P = 0.061$) G:F, with the greatest improvement at 58% SID Thr:Lys ratio and incremental improvements thereafter.. Additionally, increasing SID Thr:Lys ratio linearly decreased ($P = 0.016$) and tended to quadratically decrease ($P = 0.063$) BUN with increasing SID Thr:Lys ratio with the lowest BUN at 68% SID Thr:Lys ratio.

Combined Dose Response Curves Exp. 3 and 4

The dose-response models for Exp. 1 and 2 predicted a requirement estimate for ADG beyond the highest dose tested (68% SID Thr:Lys ratio). Thus, the greater range of SID Thr:Lys ratios was used in Exp. 3 and 4. The data from Exp. 3 and 4 was combined to develop dose response models to estimate the SID Thr:Lys requirement for 37- to 120-kg DNA 600 × 241 pigs. A QP model suggested that ADG was maximized at 68.6% SID Thr:Lys, while a similarly fitting BLL model suggested no further improvement in ADG beyond 61.1% SID Thr:Lys (Figure 2.2). A BLL model suggested no further improvement in G:F beyond 59.2% SID Thr:Lys (Figure 2.3). For BUN, a QP model suggested that BUN was minimized at 69.2% SID Thr:Lys (Figure 2.4).

Discussion

Threonine has been reported as the second limiting AA in corn-soybean meal-based diets and has been determined to be the first limiting AA for maintenance (Wang and Fuller 1989). Schaart et al. (2005) observed that 40 to 60% of dietary Thr intake is extracted by the portal drained viscera during first pass metabolism, with the majority being used by epithelial tissue for production of mucins, accounting for approximately 71% of total threonine usage (Le Floc'h and Sève, 2005; Tang et al., 2021). Threonine accounts for up to 30% of the total AAs in the mucin protein (Le Floc'h and Sève, 2005). As Thr is preferentially utilized within the GIT, it has been observed that Thr deficiency results in restricted skeletal muscle growth, while mucin production is maintained (Munasinghe et al., 2017). Additionally, as BW increases the absolute volume of the GIT increases (Elefson et al., 2021). In two studies utilizing pigs inoculated with either *Escherichia coli* or *Salmonella typhimurium*, Wellington et al. (2018, 2019b) observed that SID Thr:Lys ratios between 68 and 72% of Lys supported maximum ADG, G:F, and protein deposition during an enteric infection. These results reinforce the necessity of Thr for protein synthesis and maintenance in the intestinal tissue. Thus, as intestinal capacity, or intestinal protein turnover, increases as the pig grows, mucin production should theoretically increase as well, which has led to the hypothesis that the pigs' Thr requirement for maintenance and growth should increase with increased BW. The NRC (2012) estimates suggest that SID Thr:Lys requirements increase from 59 to 65% as BW increases from 11 to 135 kg.

Multiple studies conducted in the 1990s observed requirement estimates for total Thr:Lys ratio under 60% in 9- to 23-kg pigs (Adeola et al., 1994; Bergstrom et al., 1996; Ragland and Adeola 1996). Research conducted more recently throughout the growing-finishing period has found more varied responses. In 22- to 50-kg pigs, Zhang et al (2013) observed that ADG and G:F were maximized at 70 and 68% SID Thr:Lys, respectively, while Mathia et al. (2016) suggested that ADG and G:F were maximized at 66 and 63% SID Thr:Lys in pigs of a similar weight range. However, experiments conducted by Jayaraman et al. (2015), Remus et al. (2019), and Wellington et al., (2018, 2019a,b) observed requirement estimates ranging from 61 to 72% SID Thr:Lys to maximize ADG, G:F, and protein deposition. This variation in requirement estimates led us to further study the response to various SID Thr:Lys levels.

Similar to previous studies, we observed a wide range of requirement estimates across our first two experiments. In Exp. 1 (11 to 24 kg) we observed that ADG and G:F were maximized at > 68% and 61.8% SID Thr:Lys, respectively, based on QP models. These requirement estimates are considerably higher than results in much of the published research conducted in a similar weight range (Adeola et al., 1994; Bergstrom et al., 1996; Jayaraman et al., 2015). For early finishing pigs (43 to 70 kg) in Exp. 2, we observed that ADG and G:F were maximized at or above 67 and 65%, respectively. However, in each of our first two experiments, the highest SID Thr:Lys ratios tested (68% of Lys) may not have been high enough to obtain a clear quadratic response. As a result, we conducted Exp. 3 and 4, in which we tested a wider range of SID Thr:Lys ratios to determine requirement estimates from 37- to 120-kg pigs. Data from Exp. 3 and 4 were analyzed to determine whether the requirement for SID Thr:Lys increases with increasing BW as suggested by the NRC (2012). The absence of linear or quadratic interactions between SID Thr:Lys ratio and experiment suggests that the SID Thr:Lys requirement remains consistent for 37- to 120-kg pigs. Our dose response models suggest that ADG is maximized at 61.1 to 68.6% SID Thr:Lys and G:F is maximized at 59.2% SID Thr:Lys ratio. These results are consistent with previous research that has estimated the SID Thr:Lys requirement between 63 and 71% (Zhang et al., 2013; Mathai et al., 2016; Remus et al., 2019).

Pigs have a limited ability to store free AA, and as such excess AA are catabolized forming an end product of urea or used as an energy source (Rosell and Zimmerman, 1985; Chang et al., 2000). Thus, many studies have used BUN as a measure to estimate an AA requirement, as BUN concentrations increase in response to a deficiency, or excess, of one or more AA (Li et al., 1998; Wang et al., 2007; Zhang et al., 2013). Therefore, utilizing models to determine the SID Thr:Lys concentration required to minimize BUN can help determine the point at which pigs most efficiently synthesize protein. In Exp. 3 and 4, a QP model suggested that BUN was minimized at 69.2% SID Thr:Lys, regardless of weight range. These results are almost identical to the 68.6% SID Thr:Lys ratio that maximized ADG, and are higher than 63% SID Thr:Lys required to minimize BUN in 22- to 50-kg pigs observed by Zhang et al. (2013). These differences could be a result of genetic differences, increased BW in our studies, or greater protein accretion potential in the pigs used in our studies.

In conclusion, these results would suggest a range of SID Thr:Lys ratio requirement estimates depending on response criteria. In 37- to 120-kg pigs, our dose response models suggest that ADG is maximized at 61.1 to 68.6% SID Thr:Lys, G:F is maximized at 59.2% SID Thr:Lys ratio, and BUN is minimized at 69.2% SID Thr:Lys ratio. However, our observations that SID Thr:Lys ratio and BW did not have a linear or quadratic interaction (Exp. 3 and 4) may suggest that SID Thr:Lys requirements to maximize growth performance and minimize BUN do not increase with increasing BW.

References

Adeola, O., B. V. Lawrence, and T. R. Cline. 1994. Availability of amino acids for 10- to 20-kilogram pigs: lysine and threonine in soybean meal. J. Anim. Sci. 72:2061-2067. doi:10.2527/1994.728061x.

Bergstrom, J. R., J. L. Nelssen, M. D. Tokach, R. D. Goodband, K. Q. Owen, B. T. Richert, W. B. Richert, W. B. Nessmith, Jr., J. A. Loughmiller, and S. S. Dritz. 1996. Determining the optimal threonine:lysine ratio in diets for the phase III nursery pig. J. Anim. Sci. 74(Suppl. 1):56 (Abstr.).

Chang, W. H., J. H. Lee, K. N. Heo, I. K. Paik, and In K. Han. 2000. Optimal threonine:lysine ratio for growing pigs of different sexes. Asian-Aus. J. Anim. Sci. 13:1731-1737. doi:10.5713/ajas.2000.1731.

Elefson, S. K., N. Lu, T. Chevalier, S. Dierking, D. Wang, H. J. Moneque, J. C. Matthews, Y. D. Jang, J. Chen, G. K. Rentfrow, S. A. Adedokun, and M. D. Lindemann. 2021. Assessment of visceral organ growth in pigs from birth through 150 kg. J. Anim. Sci. 99:1-11. doi:10.1093/jas/skab249.

Jayaraman, B., J. Htoo, and C. M. Nyachoti. 2015. Effects of dietary threonine:lysine ratios and sanitary conditions on performance, plasma urea nitrogen, plasma-free threonine and lysine of weaned pigs. J. Anim. Nutr. 1:283-288. doi:10.1016/j.aninu.2015.09.003.

Le Floc'h, N., and B. Sève. 2005. Catabolism through the threonine dehydrogenase pathway does not account for the high first-pass extraction rate of dietary threonine by the portal drained viscera in pigs. Br. J. Nutr. 2005. 93:447-456. doi:10.1079/BJN20051375.

Li, D. F., C. T. Xiao, J. H. Kim, W. T. Cho, and In K. Han. 1998. Effects of crystalline lysine, threonine and tryptophan supplementation of diets containing reduced protein levels on performance of growing pigs. Asian-Aus. J. Anim. Sci. 11:43-50. doi:10.5713/ajas.1998.43.

NRC. 2012. Nutrient requirements of swine: 11th ed. Natl. Acad. Press, Washington, DC.

Mathai, J. K., J. K. Htoo, J. E. Thomson, K. J. Touchette, and H. H. Stein. 2016. Effects of dietary fiber on the ideal standardized ileal digestible threonine:lysine ratio for twenty-five to fifty kilogram growing gilts. J. Anim. Sci. 94:4217-4230. doi:10.2527/jas2016-0680.

Munasinghe, L. L., J. L. Robinson, S. V, Harding, J. A. Brunton, and R. F. Bertolo. 2017. Protein synthesis in mucin-producing tissues is conserved when dietary threonine is limiting in piglets. J. Nutr. 147:202-210. doi:10.3945/jn.116.236786.

PIC. 2021. PIC Nutrition and feeding guidelines. [accessed June 28, 2024]. https://www.pic.com/wp-content/uploads/sites/3/2021/03/PIC-Nutition-Manual_English-Imperial.pdf

Ragland, D., and O. Adeola. 1996. The response of 10-kg pigs to increasing dietary threonine levels. J. Anim. Sci. 74(Suppl. 1):55 (Abstr.).

Remus, A., L. Hauschild, E. Corrent, M. Létourneau-Montminy, and C. Pomar. 2019. Pigs receiving daily tailored diets using precision-feeding techniques have different threonine requirements than pigs fed in conventional phase-feeding systems. J. Anim. Sci. Biotechnol. 10:16. doi:10.1186/s40104-019-0328-7.

Rosell, V. L., and D. R. Zimmerman. 1985. Threonine requirement of pigs weighing 5-15 kg and the effect of excess methionine in diets marginal in threonine. J. Anim. Sci. 60:480-486. doi:10.2527/jas1985.602480x.

Royall, R. Q., R.D. Goodband, M. D. Tokach, J. M. DeRouchey, J. C. Woodworth, and J. T Gebhardt. 2022. Effects of standardized ileal digestible lysine level on growth performance and economic return for 18 to 128 kg Duroc-sired pigs. Transl. Anim. Sci. 6:4. doi:10.1093/tas/txac103.

Schaart, M. W., H. Schierbeek, S. R. D. van der Schoor, B. Stoll, D. G. Burrin, P. J. Reeds, and J. B. van Goudoever. 2005. Threonine utilization is high in the intestine of piglets. J. Nutr. 135:765-770. doi:10.1093/jn/135.4.765.

Tang, Q. P. Tan, N. Ma, and X. Ma. 2021. Physiological functions of threonine in animals: beyond nutrition metabolism. Nutrients. 13:2592. doi:10.3390/nu13082592.

Wang, T. C., and M. F. Fuller. 1989. The optimum dietary amino acid pattern for growing pigs. Br. J. Nutr. 62:77-89. doi:10.1079/bjn19890009.

Wang, X., S. Qiao, Y. Yin, L. Yue, Z. Wang, and G. Wu. 2007. A deficiency or excess of dietary threonine reduces protein synthesis in jejunum and skeletal muscle of young pigs. J. Nutr. 137:1442-1446. doi:10.1093/jn/137.6.1442.

Wellington, M. O., J. K. Htoo, A. G. Van Kessel, and D. A. Columbus. 2018. Impact of dietary fiber and immune system stimulation on threonine requirement for protein deposition in growing pigs. J. Anim. Sci. 96:522-5232. doi:10.1093/jas/sky381.

Wellington, M. O., J. K. Htoo, A. G. Van Kessel, and D. A. Columbus. 2019a. Estimating the optimal threonine requirement for 25-50 kg pigs fed a mixture of soluble and insoluble dietary fibre. Can. J. Anim. Sci. 99:634-638. doi:10.1139/cjas-2018-0218.

Wellington, M. O., A. K. Agyekum, K. Hamonic, J. K. Htoo, A. G. Van Kessel, and D. A. Columbus. 2019b. Effect of supplemental threonine above requirement on growth performance of *Salmonella typhimurium* challenged pigs fed high-fiber diets. J. Anim. Sci. 97:3636-3647. doi:10.1093/jas/skz225.

Zhang, G. J., C. Y. Xie, P. A. Thacker, J. K. Htoo, and S. Y. Qiao. 2013. Estimation of the ideal ratio of standardized ileal digestible threonine to lysine for growing pigs (22-50 kg) fed low crude protein diets supplemented with crystalline amino acids. J. Anim. Feed Sci. 180:83-91. doi:10.1016/j.anifeedsci.2013.01.006.

Table 2.1 Diet composition (as-fed basis)

	Exp. 1[1]		Exp. 2[2]		Exp. 3[3]		Exp. 4[4]	
SID Thr:Lys, %	53	68	53	68	53	78	53	78
Ingredient, %								
Corn	64.86	64.67	78.39	78.17	79.56	79.33	90.08	89.77
Soybean meal	30.00	30.00	18.70	18.80	17.18	17.19	7.32	7.49
Choice white grease	1.45	1.45	---	---	---	---	---	---
Monocalcium P, 21% P	0.87	0.87	0.45	0.45	1.30	1.30	0.80	0.80
Limestone	1.00	1.02	1.18	1.18	0.75	0.75	0.83	0.83
Sodium chloride	0.61	0.61	0.55	0.55	0.50	0.50	0.50	0.50
L-Lys-HCl	0.36	0.36	0.28	0.28	0.31	0.31	0.28	0.28
DL-Met	0.23	0.23	0.11	0.11	0.07	0.07	---	---
L-Thr	0.03	0.20	---	0.12	---	0.22	---	0.14
L-Trp	0.02	0.02	0.01	0.01	0.03	0.03	0.03	0.03
L-Val	0.13	0.13	0.04	0.04	0.02	0.02	---	---
Vitamin premix[6]	0.25	0.25	0.15	0.15	---	---	---	---
Vitamin premix	---	---	---	---	0.15	0.15	0.10	0.10
Trace mineral premix	0.15	0.15	0.15	0.15	0.15	0.15	0.08	0.08
Copper sulfate	0.06	0.06	---	---	---	---	---	---
Total	100	100	100	100	100	100	100	100
Calculated analysis								
SID AA, %								
Lys, %	1.15	1.15	0.81	0.81	0.84	0.84	0.58	0.58
Ile:Lys	56	56	59	59	61	61	60	60
Leu:Lys	119	119	131	131	144	144	170	170
Met and Cys:Lys	59	59	59	59	60	60	62	62
Thr:Lys	53	68	53	68	53	78	53	78
Trp:Lys	20	20	19.2	19.2	19.7	19.7	19.3	19.4
Val:Lys	70	70	70	70	71	71	73	73
His:Lys	36	36	37	37	42	42	45	46
NE, kcal/kg	2,449	2,449	2,471	2,471	2,500	2,500	2,571	2,571
SID Lys:NE, g/Mcal	4.70	4.70	3.28	3.28	3.36	3.36	2.26	2.26
CP, %	18.7	18.8	14.2	14.3	15.1	15.3	11.2	11.4
Ca, %	0.69	0.70	0.64	0.64	0.66	0.66	0.54	0.54
STTD P, %	0.44	0.44	0.33	0.33	0.44	0.44	0.26	0.26

[1] Diets were fed from 11.8 to 24.0 kg BW. The two diets were blended to create intermediate treatment diets containing 58, 62, and 65% SID Thr:Lys ratio.

[2] Diets were fed from 43.4 to 70.0 kg BW. The two diets were blended to create intermediate treatment diets containing 58, 62, and 65% SID Thr:Lys ratio.

[3] Diets were fed from 37.4 to 69.6 kg BW. The two diets were blended to create intermediate treatment diets containing 58, 63, 68, and 73% SID Thr:Lys ratio.

[4] Diets were fed from 96.2 to 120.4 kg BW. The two diets were blended to create intermediate treatment diets containing 58, 63, 68, and 73% SID Thr:Lys ratio.

[5] THR Pro; CJ America-Bio, Downers Grove, IL.

[6] Axtra PHY (Dupont, Wilmington, DE) provided 717, 430, and 520 phytase units (FTU/kg) for an estimated release of 0.13, 0.12, and 0.14% STTD P, in Exp. 1, 2, and 3, respectively.

Table 2.2. Amino acid analysis of diets (as-fed basis)[1]

	Exp. 1[2]		Exp. 2[2]		Exp. 3[2]						Exp. 4[3]					
SID Thr:Lys, %	53	68	53	68	53	58	63	68	73	78	53	58	63	68	73	78
Amino acid analysis, %[2]																
Lys	1.17	1.17	0.90	0.98	0.87	0.90	0.92	0.92	0.97	0.90	0.63	0.69	0.73	0.66	0.68	0.71
Ile	0.73	0.70	0.55	0.59	0.53	0.53	0.53	0.54	0.52	0.52	0.39	0.44	0.41	0.42	0.40	0.41
Leu	1.65	1.48	1.26	1.31	1.31	1.25	1.28	1.31	1.27	1.26	1.00	1.10	1.08	1.08	1.04	1.07
Met	0.40	0.48	0.30	0.41	0.30	0.30	0.30	0.30	0.29	0.29	0.19	0.21	0.22	0.19	0.19	0.20
Met + Cys	0.71	0.74	0.51	0.64	0.53	0.53	0.53	0.54	0.52	0.52	0.37	0.41	0.41	0.38	0.38	0.40
Thr	0.73	0.83	0.55	0.72	0.53	0.58	0.61	0.68	0.70	0.73	0.36	0.42	0.45	0.45	0.47	0.52
Trp	0.21	0.25	0.18	0.20	0.17	0.16	0.21	0.16	0.17	0.18	0.11	0.10	0.11	0.10	0.09	0.09
Val	0.87	0.88	0.65	0.74	2.16	2.11	2.12	2.09	2.11	2.11	0.48	0.53	0.53	0.51	0.51	0.53
His	0.46	0.45	0.37	0.38	0.36	0.36	0.36	0.37	0.37	0.36	0.29	0.31	0.29	0.30	0.28	0.29

[1] Diet samples were taken from all feeders approximately 3 d after the beginning of the trial and stored at -20°C. Values are reported on a total analyzed basis.

[2] Composite samples were submitted to Ajinomoto Heartland Inc. (Eddyville, IA) for amino acid analysis.

[3] Composite samples were submitted to University of Missouri-Columbia Agricultural Experiment Station Chemical Laboratories (Columbia, MO) for amino acid analysis

Table 2.3**.** Effects of increasing SID Thr:Lys ratio on growth performance of 11- to 24-kg pigs, Exp. 1[1]

	SID Thr:Lys ratio, %						*P* =	
Item:	53	58	62	65	68	SEM	Linear	Quadratic
BW, kg								
d 0	12.0	11.7	11.8	11.6	11.9	0.32	0.554	0.111
d 21	23.1	23.7	24.1	24.0	24.5	0.41	0.005	0.766
Growth performance								
ADG, g	527	547	563	569	585	10.8	< 0.001	0.948
ADFI, g	847	780	782	787	870	21.2	0.599	< 0.001
G:F, g/kg	622	706	726	729	673	23.1	0.007	< 0.001

[1] A total of 987 pigs (PIC 337 × 1050, initially 11.8 ± 0.32 kg) were used in a 21-d growth performance study with 22 to 27 pigs per pen and 8 replications per treatment.

Table 2.4. Effects of increasing SID Thr:Lys ratio on growth performance of 43- to 70-kg pigs, Exp. 2[1]

	SID Thr:Lys ratio, %						*P* =	
Item:	53	58	62	65	68	SEM	Linear	Quadratic
BW, kg								
d 0	43.3	43.6	43.3	43.3	43.3	0.58	0.841	0.958
d 28	68.5	68.6	69.0	69.8	70.0	0.80	0.037	0.510
Growth performance								
ADG, g	900	898	914	947	942	16.6	0.020	0.524
ADFI, kg	2.09	2.05	2.10	2.10	2.13	0.031	0.214	0.325
G:F, g/kg	431	438	435	450	443	5.1	0.027	0.841

[1] A total of 875 pigs (PIC 337 × 1050 initially 43.4 ± 0.58 kg) were used in a 28-d growth performance study with 21 to 27 pigs per pen and 7 replication per treatment.

Table 2.5. Effects of increasing SID Thr:Lys ratio on growth performance of 37- to 70-kg pigs, Exp. 3[1]

	SID Thr:Lys ratio, %							*P* =	
Item:	53	58	63	68	73	78	SEM	Linear	Quadratic
BW, kg									
Initial	37.4	37.4	37.4	37.4	37.4	37.4	1.36	0.990	0.884
Final	67.7	68.9	69.4	69.6	69.2	69.2	0.88	0.030	0.025
Growth Performance									
ADG, g	960	994	1,017	1,022	1,008	1,009	12.3	0.004	0.005
ADFI, kg	2.22	2.22	2.24	2.24	2.23	2.18	0.036	0.530	0.256
G:F, g/kg	432	450	454	457	453	463	4.1	< 0.001	0.047
Blood urea nitrogen, mg/dL[2]	7.26	7.17	7.13	6.88	7.08	7.14	0.205	0.215	0.093

[1] Two groups of pigs were used in studies lasting 35 and 28 d, respectively, for a total of 684 pigs (DNA 600 × 241; initially 37.4 ± 1.36)
with 9 or 10 pigs per pen and 12 replications per treatment.

[2] Blood samples were taken on d 14 from 3 pigs per pen (2 barrows and 1 gilt).

Table 2.6. Effects of increasing SID Thr:Lys ratio on growth performance of 96- to 120-kg pigs, Exp. 4[1]

	SID Thr:Lys ratio, %							*P* =	
Item:	53	58	63	68	73	78	SEM	Linear	Quadratic
BW, kg									
Initial	96.2	96.3	96.2	96.2	96.2	96.2	1.04	0.962	0.985
Final	118.8	119.5	120.0	120.4	119.8	119.8	1.07	0.136	0.061
Growth performance									
ADG, g	801	831	850	863	839	850	19.7	0.035	0.063
ADFI, kg	2.82	2.82	2.84	2.89	2.91	2.85	0.038	0.114	0.301
G:F, g/kg	284	295	299	298	288	298	5.2	0.106	0.061
Blood urea nitrogen, mg/dL[2]	6.67	6.52	6.39	6.34	6.42	6.40	0.150	0.016	0.059

[1] Two groups of pigs were used in 28 d studies, for a total of 662 pigs (DNA 600 × 241; initially 96.2 ± 1.04 kg) with 8 to 10 pigs per pen and 11 or 12 replications per treatment.

[2] Blood samples were taken on d 13 and 14, group 1 and 2, respectively, from 3 pigs per pen (2 barrows and 1 gilt).

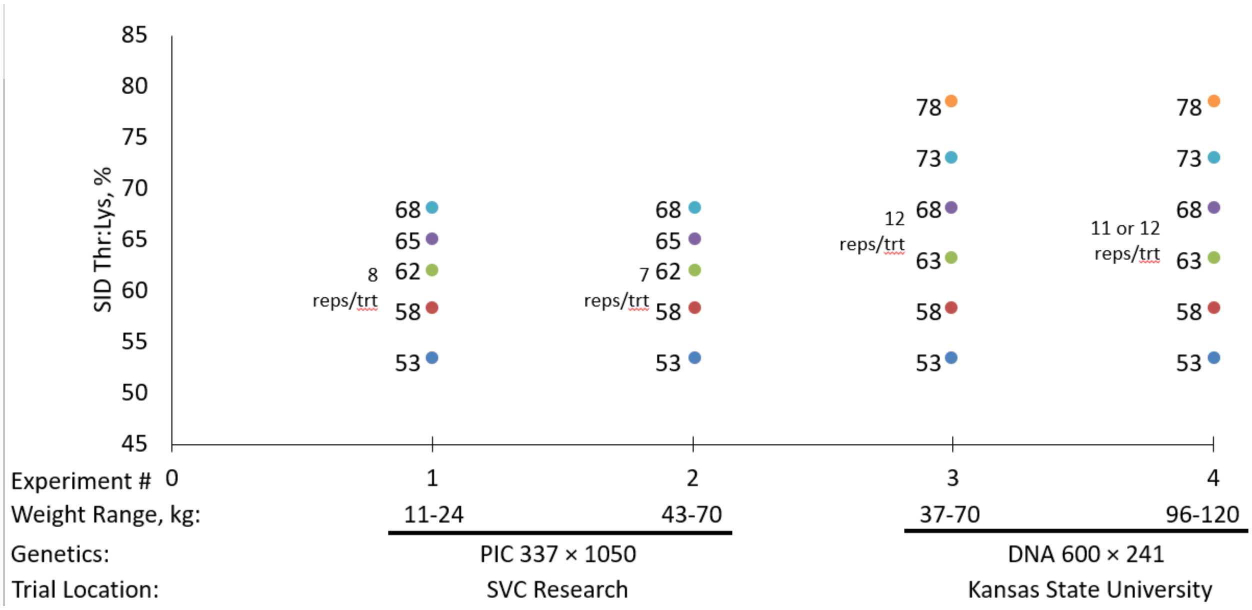


Figure 2.1 Summary of weight range, range of SID Thr:Lys ratio tested, genetic background of pigs, and location of each experiment.

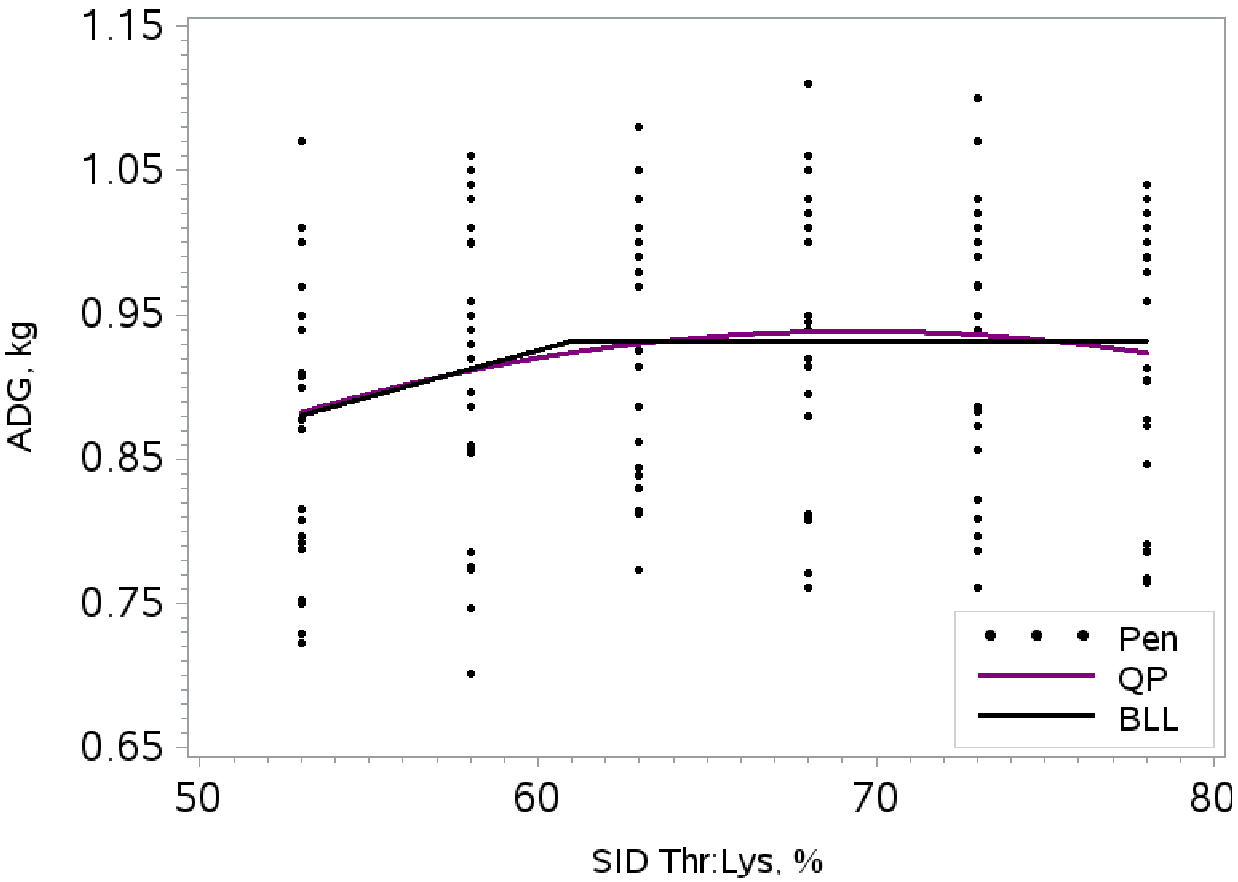


Figure 2.2 Estimation of SID Thr:Lys ratio requirements to maximize ADG for 37- to 120-kg DNA 600 × 241 pigs, Exp. 3 and 4.

The QP and BLL models resulted in the best fit, based BIC (BIC = -386.2 vs. -386.7, QP vs. BLL). The QP model predicted 95 and 100% of maximum ADG at 53.7 and 68.6% SID Thr:Lys, respectively. The developed QP model equation for ADG was: ADG = -0.00021 × (SID Thr:Lys, %)^2 + 0.02881 × (SID Thr:Lys, %) – 0.06193. The BLL model predicted no further improvement beyond 61.1% SID Thr:Lys.

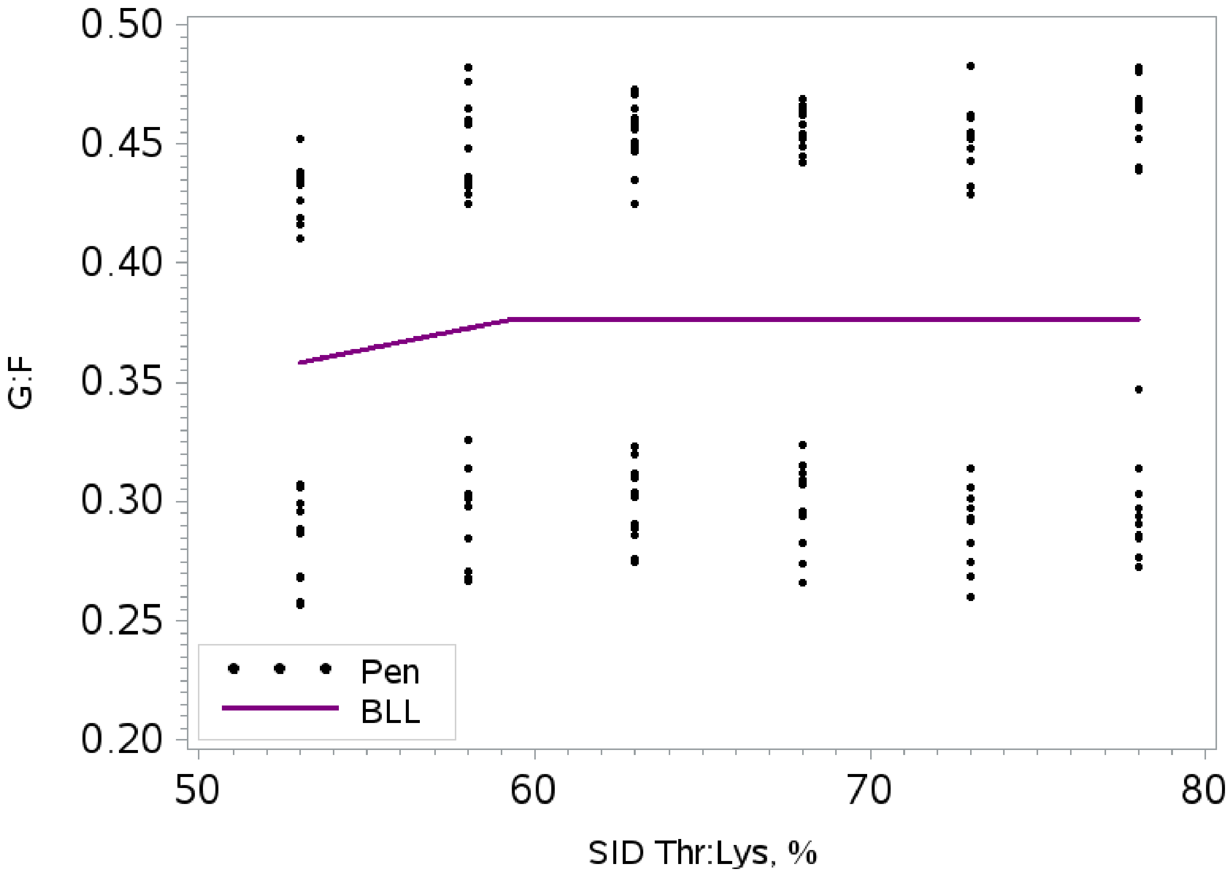


Figure 2.3. Estimation of SID Thr:Lys ratio requirements to maximize G:F for 37- to 120-kg DNA 600 × 241 pigs, Exp. 3 and 4.

The BLL model resulted in the best fit, based on BIC. The BLL model predicted no further improvement beyond 59.2 % SID Thr:Lys.

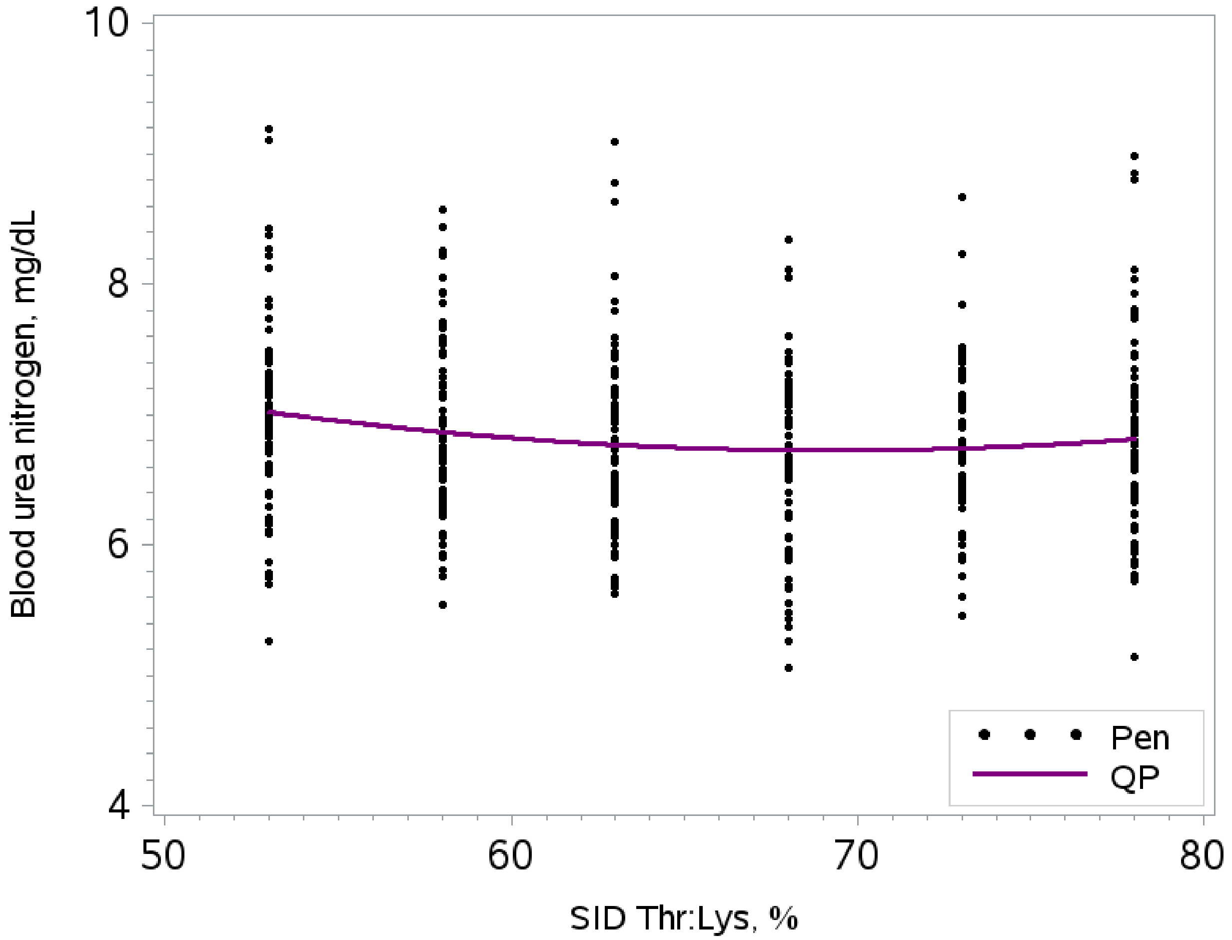


Figure 2.4. Estimation of SID Thr:Lys ratio requirements to minimize BUN for 37- to 120-kg DNA 600 × 241 pigs, Exp. 3 and 4.

The QP model resulted in the best fit, based on BIC. The QP model predicted 95 and 100% of minimum BUN at 51.9 and 69.2% SID Thr:Lys, respectively. The developed QP model equation for BUN was: BUN mg/dL = 0.001121 × (SID Thr:Lys, %)^2 – 0.1552 × (SID Thr:Lys, %) + 12.0988.

Chapter 3 - Defining the ideal soybean meal usage in finishing swine diets: A review

Abstract

Soybean meal (SBM) is the predominant protein and amino acid (AA) source used in swine diets in the U.S. In addition to providing high concentrations of an easily digestible profile of AAs, SBM is a source of dietary energy and contains biologically active compounds which may enhance swine health and growth performance. However, economics (i.e., reduced diet costs) can lead to swine nutritionists replacing a portion or all the SBM in the diet with feed-grade AAs and other intact protein sources. The objective of this literature review was to determine if a minimum SBM concentration exists to maintain high growth performance of growing-finishing pigs in various dietary and environmental situations. Based on the literature, when formulating corn-based, AA supplemented diets to meet current NRC (2012) requirement estimates, it appears that feeding at least 10.0% SBM and 12% CP allows for acceptable growth performance of 20- to 85-kg pigs when feed-grade AA are available. However, in finishing pigs (> 100 kg), reducing SBM and CP below 8.8% 11.8%, respectively, reduces growth performance despite added AA. The addition of other intact protein sources to the diet brings with it a variety of accompanying concerns, most notably dietary fiber content and the associated reduction in dietary NE. Partially replacing SBM with DDGS has its limitation as growth performance is reduced when DDGS exceeds 20 or 30% of the diet even though AA and N content are maintained above the pigs' requirement. However, it has been shown that it is possible to maintain growth performance when removing SBM in diets containing DDGS when dietary NE and N are provided at adequate levels. During times of heat stress, there is no data to support the need to lower SBM levels in the diet. During a respiratory disease challenge, data suggests that increasing dietary SBM can improve growth performance and reduce mortality. A greater understanding of the immuno-supportive functions of SBM remains an important area for growth and research in the face of current disease pressure.

Key Words: Amino acids, crude protein, grow-finish pig, soybean meal

Introduction

Soybean meal (SBM) accounts for 71% of the worldwide protein meal consumption and is the predominant protein source used in U.S. swine diets due to its highly digestible amino acid (AA) profile (Stein et al., 2008; Soy Stats, 2022). These and other characteristics make SBM a high quality and economical AA source for swine. Yet in some cases, nutritionists may formulate swine diets with feed-grade AAs, or other intact protein sources as complete or partial replacement of SBM to reduce diet cost. Research results on the maximum amounts of feed-grade AA that can replace SBM suggests that a minimum CP or non-essential AA concentration is needed in the diet (> 12.0% CP). On the other hand, most alternative protein sources used in swine diets contain less essential AA (EAA's) and more fiber compared to SBM, which limits the availability of EAAs and energy intake resulting in negative effects on growth performance and carcass characteristics (Cromwell et al., 2011; Little et al., 2015).

Heat stress can not only be caused by periods of high ambient temperatures, but also by heat increment from consuming higher protein or fiber diets. Thus, partially replacing SBM with feed-grade AA to lower the diet CP level would potentially lower the heat increment of the diet (Kerr et al., 2003; de Oliveira et al., 2023). However, this potential reduction in heat increment has not necessarily been shown to improve growth, perhaps due to a greater NE content in SBM than previously thought (Cemin et al., 2020) and lower fiber content compared to other intact protein sources such as DDGS. These factors need to be considered when determining the relative value of alternative protein sources as complete or partial replacements of SBM in times of heat stress.

A unique characteristic of SBM is the presence of biologically active compounds (isoflavones, saponins, peptides, and omega-3 fatty acids) which have been observed to possess anti-inflammatory, antioxidative, and anti-viral properties (Omoni and Aluko, 2005; Smith and Dilger, 2018; Smith et al., 2020). While the mechanisms by which these compounds improve immune response and growth performance during a disease challenge are not fully understood, their effects cannot be ignored when determining the use of SBM in growing-finishing pig diets (Boyd et al., 2010; Rochell et al., 2015; Smith et al., 2020).

The balance between reducing diet cost and maintaining growth performance is important for the profitability of swine producers. The objective of this review was to summarize the current literature and attempt to determine the minimum SBM concentration to maintain high growth performance of growing-finishing pigs for the following circumstances: 1) low-protein, AA-fortified diets as a replacement for SBM, 2) use of one or more alternative protein sources in combination with SBM, 3) during periods of heat stress, and 4) during periods of disease challenge. Our hypothesis is that through a review of the literature, we could identify a need to have a minimum amount of SBM in the diet for growing-finishing pigs.

Materials and Methods

Data Source

The online article databases used for this literature review were the Centre for Agriculture and Bioscience International (CABI; CAB Direct), PubMed, and the Soybean Meal

Info Center. Articles were identified using the following terms: pig, finishing pig, swine, soybean meal, amino acids, crude protein, synthetic amino acids, crystalline amino acids, distillers dried grains with solubles, canola meal, rapeseed meal, peas, faba beans, net energy, heat stress, isoflavones, disease, and immune system. The language of the articles was limited to English, and the article types were limited to peer-reviewed publications and university research reports. Once relevant articles were identified, they were filed and categorized according to topic for further evaluation.

Inclusion and Exclusion Criteria

Research articles were included if they met the following criteria: 1) the study was an original randomized controlled *in vivo* study; 2) pigs on all treatments within study had a similar starting live body weight greater than 20 kg with an identical (fixed-time study) or similar (fixed-weight study) experimental period; 3) complete diet formulations were included in the article, dietary treatments contained varying levels of SBM, and all diets were formulated to either a constant total, AID, or SID Lys percentage when applicable, or a constant Lys:calorie ratio, and 4) the study reported means and statistical analysis for growth performance (ADG, ADFI, and G:F) The exclusion criteria were: 1) duplicate search results; 2) data duplication between different research articles; 3) the article did not provide numeric values of the results, or 4) the original full text of the article could not be retrieved. Papers selected for this review were published between 1994 and 2024.

Diets

To compare results from different experiments used in this review, dietary treatments within each trial were reformulated using the NRC (2012) nutrient loading values and digestibility coefficients for ingredients to standardize dietary nutrient concentrations. Calculated analysis of SID AA and total N were compared to NRC (1998; 2012) requirement estimates based on when the trial was completed to determine if AAs were provided at or above the pig's requirement estimate. This information was then used to evaluate potential limiting nutrients within each trial.

Results and Discussion

Optimal SBM level in low protein-amino acid fortified diets where SBM is the only intact protein source

The widespread availability and competitive prices of feed-grade AAs, coupled with the ability to formulate to meet individual AA requirements while reducing N excretion, has resulted in their partial or complete replacement of SBM in swine diets. However, research on the maximum amounts of feed-grade AA that can replace SBM has yielded variable results. For each trial evaluating low-protein, AA-fortified diets within this review, a summary was compiled of: 1) major ingredients used in experimental diets, 2) BW range, 3) SBM range tested, 4) associated CP range tested, 5) minimum SBM level required to support optimum ADG, 6) minimum SBM level required to support optimum G:F, and 7) the potential first limiting nutrient in diets that resulted in decreased growth performance based on revised diet formulation (Table 1).

Growing pigs. Several studies have indicated that partial replacement of SBM with feed-grade AAs had no effect on growth performance in the grower phase (20- to 85-kg) when SBM was held at or above 10% of the diet (Kerr et al., 1995; Tuitoek et al., 1997; Stein et al., 2024; Table 1). Whereas reducing SBM and CP below 10 and 13%, respectively, has shown a negative effect on performance even with additions of L-Lys, DL-Met, L-Thr, and L-Trp (Figueroa et al., 2002; Gómez et al., 2002; Duarte et al., 2024), likely because of Val, Ile, or N deficiency.

Faccin et al. (2023) observed that reducing SBM to 19.1% of the diet decreased ADG and G:F compared to diets with 22.6% SBM or greater, in 43- to 72-kg pigs. Similarly, Giacomini et al. (2024) observed that reducing SBM to 17.5% of the diet reduced G:F compared to diets with 23.3% SBM or greater, in 32- to 59-kg pigs. However, recent studies by Duarte et al. (2024) observed that reducing SBM from 25 to 19% of the diet in 20- to 40-kg pigs did not reduce growth performance, while a second study in 34- to 55- kg pigs observed a reduction in G:F when SBM was reduced from 15.6 to 8.9% of the diet. While this amount of SBM is well above the level shown to reduce growth performance in other studies (10%), this may indicate that another factor within SBM has a positive influence on grower pig performance. One possible explanation may be biologically active compounds within SBM that lead to beneficial growth responses (Omoni and Aluko, 2005; Smith and Dilger, 2018). Additionally, increases in growth rate and protein accretion rates of modern pigs may have increased AA and N requirements, thus increasing the level of SBM needed in the diet.

Figueroa et al. (2002) observed that it is possible to reduce SBM inclusion to 8% of the diet; however, they used SBM with 49% as compared to other experiments in the literature with SBM containing less than 48% CP. Reducing SBM below 12.3 and 11.5% in corn-SBM diets appears to result in deficiencies in Thr and Val, respectively, based on NRC (2012) requirement estimates. However, when feed-grade Lys, Met, Thr, Trp, and Val are utilized, it appears that a minimum threshold of at least 10% SBM should be used in low-protein, AA-fortified diets for growing pigs (20 to 85 kg).

Finishing pigs. During the early finishing period (80- to 100 -kg), Kerr et al. (1995) added L-Lys, L-Thr, and L-Trp and observed that reducing SBM from 15.7 to 8.1%

(corresponding to 14 to 11% CP) did not affect growth performance. However, reducing SBM below 8.1% has resulted in reduced growth performance (Tuitoek et al., 1997; Lee et al., 2001).

Liu et al. (2023) fed 16.5, 7.4 or 0.0% SBM, while maintaining SID Met and Cys, Thr, Trp, Val, Ile, His, and Phe ratios relative to Lys above NRC (2012) requirement estimates by using feed-grade AA. Although the differences were not statistically significant, decreasing SBM from 16 to 0% decreased ADG and G:F by 6.2 and 7.1%, respectively with the greatest response observed as SBM decreased from 7.4 to 0%. This resulted in a decrease in SID N intake from 45 to 34 g/d, likely resulting in a N deficiency (40.2 g/d; NRC 2012).

During late finishing (> 100 kg), data has demonstrated that diets can be formulated with reduced SBM compared to the grower stage through the aggressive use of feed-grade AA and meet the nutrient requirement estimates. Soto et al. (2019) and Holen et al. (2022) observed that reducing SBM below 8.8% of the diet, with an accompanying reduction in CP below 11.8%, resulted in reduced performance likely as a result of deficient SID Phe, Arg or N. Knowles et al. (1998) fed diets containing 20.1 vs 10.7% SBM (11.7% CP) and observed decreased G:F with the lower SBM level. No differences in growth performance were observed in pigs fed low-protein diets when they contained at least 11.2% SBM and 13.1% CP (Royall et al., 2022; Faccin et al., 2023). De la Llata et al. (2002) decreased SBM and added only L-Lys HCl in sorghum- or corn-SBM-based diets and observed that adding greater than 0.15% L-Lys decreased ADG and G:F. This would have corresponded to less than 7.5 or 11.1% SBM in sorghum- and corn-based diets, respectively. However, this appears to be a result of a deficiency in SID Thr or other amino acids.

Reductions in growth performance when high levels of feed-grade AAs are used to replace SBM might be linked to insufficient SID N intake (g/day). Data from Knowles et al.

(1998), Soto et al. (2019), and Holen et al. (2022) suggest reduced growth performance of 100 kg pigs when SID N intake dropped below 44 g N intake/d.

In summary, reducing SBM below 12.3 and 11.5% in corn-SBM diets appears to result in deficiencies in Thr and Val, respectively, in grower pigs based on NRC (2012) requirement estimates (De la Llata et al., 2002; Figueroa et al., 2002). However, when feed-grade Lys, Met, Thr, Trp and Val are utilized, maintaining SBM at or above 10.0% is recommended. Meanwhile, in the late-finisher period maintaining SBM and CP concentrations above 8.8 and 11.8%, respectively, allows pigs to maintain growth performance. The negative effect on performance seen below these levels may be a result of a deficiency in another EAA (i.e., Arg or Phe), or SID N intake.

Diets containing multiple protein sources to replace SBM

Evaluation of alternative protein sources relative to SBM to lower feed cost has led to research evaluating their effects on pig performance (Little et al., 2015). Most alternative intact protein sources brings formulation challenges due to being lower in CP and digestibility of AAs and lower in energy concentration than SBM. Soybean meal also contains bioactive compounds that are not present in alternative protein sources. Nevertheless, potential economic advantages of feeding other intact protein sources necessitate defining an optimum SBM level in these diets. For each trial evaluating alternative protein sources as replacement for SBM within this review, a summary table was compiled similar to Table 1, with the addition of the alternative protein sources used for replacement of SBM (Table 2).

Oilseed by-products and legumes. Ingredients that are products of oilseed extraction (i.e., canola or rapeseed meal) may have some viability as alternative protein sources to SBM. Little et al. (2015) observed that reducing SBM from 27 to 0%, via replacement with conventional canola meal on an SID Lys basis, did not affect growth performance of 27- to 57-kg pigs. However, in 57- to 87- and 87- to 115- kg pigs, reducing SBM from 21 to 0% and 18 to 0% of the diet, respectively, linearly increased ADFI and decreased G:F. However, reducing SBM from 21 to 0% and from 18 to 0% of the diet, via increased high protein canola meal, did not affect G:F. This apparent discrepancy in results is likely due to the lower fiber content of high protein canola meal compared to conventional canola meal, as there was a less pronounced reduction in NE (approximately 2%) when replacing SBM with high protein canola meal. Yun et al. (2018) observed a similar response when evaluating the effect of reducing SBM from 22 to 18% by replacing it with either canola meal or rapeseed meal in 50- to 117-kg pigs and observed no difference in growth performance. Recent studies (He et al., 2023; Zhan et al., 2024) have studied the effects of complete replacement of SBM with a combination of rapeseed meal, cottonseed meal, and sunflower seed meal in the diets of 25- to 50-kg and 51- to 78-kg pigs. In each study these authors observed that ADG, ADFI, and G:F were not reduced even when SBM was reduced to 0% of the diet (He et al., 2023; Zhan et al., 2024). This would suggest SBM can be completely replaced by these protein sources when AA and NE levels are held constant across diets. Other oilseed by-products such as camelina meal may have a more negative effect on performance. Hilbrands et al. (2021) fed 0, 5, 10, and 15% camelina meal at the expense of SBM on an equal SID Lys basis and observed a linear decrease in ADG, ADFI, final BW, and HCW. These results may have been due to the presence of anti-nutritional compounds (trypsin inhibitors and glucosinolates) found in camelina meal, which are known to reduce intake and therefore weight gain. Another potential cause would be reductions in dietary NE content when SBM was replaced with camelina meal.

Grain legumes, such as faba beans and peas, have long been considered as an alternative protein source to SBM (Castell, 1976). Smith et al. (2013) observed that reducing or completely replacing SBM with peas or faba beans did not affect growth performance during the grower phase (30- to 60-kg). However, from 60- to 100-kg, decreasing SBM reduced ADG and G:F suggesting that peas or faba beans were not a suitable replacement for SBM in late finishing; however, the reason for this reduction was unclear.

The results of these studies illustrate the potential negative effect of feeding alternative protein ingredients high in fiber content or anti-nutritional factors. It appears that the displacement of SBM with greater than 10% camelina meal, or 15% peas or faba beans reduces growth performance in growing-finishing pigs. This reduced performance appears to be primarily due to the lower NE and increased NDF content of these alternative protein sources compared to SBM (Smith et al., 2013; Little et al., 2015).

Corn distillers dried grains with solubles.

Growing pigs. Distillers dried grains with solubles (DDGS) are a by-product of the ethanol industry and are commonly used to replace a portion of corn and SBM in swine diets. In a review of the literature, Stein and Shurson (2009) concluded that up to 30% DDGS resulted in similar growth performance to a corn-soybean meal-based diet. However, over time, ethanol plants are extracting more oil from DDGS, thus concentrating NDF and lowering its NE value (Graham et al., 2014). This change in composition appears to adversely affect growth performance and needs to be considered when interpreting results of more recent DDGS studies. Linneen et al. (2008) reduced SBM from 24.3 to 22.3%, by increasing DDGS (0, 10, 20 and 30% of the diet), and observed linear decreases in ADG and ADFI. In a second experiment by Linneen et al. (2008) and in an experiment by Widmer et al. (2008), adding 15 to 20% DDGS and reducing SBM from 28.5 to 19.3% of the diet did not affect growth performance. The DDGS used in the second study by Linneen et al. (2008) and Widmer et al. (2008) contained a greater oil content, which may have supported growth performance when increasing to higher dietary DDGS concentrations. Recent studies by Lazaga et al. (2024a,b) reduced SBM via increasing low oil DDGS (6 and 3% oil, respectively; at 0, 10, 20, and 30% of the diet in both studies) and observed that this replacement linearly reduced both ADG and G:F. When DDGS exceeded 20% of the diet and SBM decreased to 12.0% (Cromwell et al., 2011) or 4.2%, (Tolosa et al., 2022) growth performance decreased. This could be related to the NDF level in these diets as diets containing at least 20% DDGS generally contain greater than 12.4% NDF, which may have been the cause of the reduction in ADFI and ADG (Linneen et al., 2008; Cromwell et al., 2011; Tolosa et al., 2022). The reduction in performance in these trials is more likely due to high DDGS and not due to low SBM content, as SBM was maintained above 10%, which was found to be sufficient for maintaining growth performance (Linneen et al., 2008; Cromwell et al., 2011).

Finishing pigs. Increased gastrointestinal tract capacity in finishing pigs may allow pigs to overcome the reduced energy intake that results from feeding high concentrations of DDGS compared to grower pigs. Widmer et al. (2008) fed diets with 0, 10, or 20% DDGS reducing SBM from 21.6 to 12.8% and from 15.1 to 5.9% of the diet in 61- to 100-kg and 100- to 127-kg pigs, respectively. In each period, replacing SBM with 20% DDGS resulted in similar or better performance to those pigs fed the diet without DDGS. White et al. (2009) reduced SBM from 14.3 to 10.9% of the diet, while increasing DDGS from 0 to 40% in 100- to 126-kg pigs and observed no changes in performance. While diets in this study were formulated to a constant AID Lys level, reformulating diets revealed that SID Lys and NE slightly increased with increasing DDGS, due to the high oil content of DDGS used in their study. This would possibly explain why growth performance was not reduced when pigs were fed high levels of DDGS.

Inclusion of 0, 15, 30, or 45% DDGS (7.6% oil), and reducing SBM to 10.4% and 6.9% (early- and late-finishing phases, respectively) linearly decreased ADG and G:F of 69- to 130-kg pigs (Graham et al., 2014). This response appears to be a result of a 1 to 3% reduction in NE when replacing SBM with DDGS. Lerner et al., (2020 a,b) reduced SBM below 6.5% of the diet, with 30 or 35% DDGS, and observed reduced growth performance. Tolosa et al. (2022) reduced SBM to 1.4% and 5.7%, via the inclusion of 30 or 15% DDGS, in 82- to 108-kg and 108- to 135-kg pigs, respectively. They observed that decreasing SBM increased ADG and ADFI by 1.04 and 4.56%, respectively, resulting in a 3.07% decrease in G:F in 85-to 137-kg pigs. This decrease in G:F is most likely the result of increasing NDF to 14.3% with the inclusion of DDGS. Moreover, Lazaga et al., (2024a,b) observed that reducing SBM via the inclusion of low oil DDGS (6 and 3% oil, respectively; at 0, 10, 20, and 30% of the diet in both studies) linearly reduced ADG and G:F with each reduction in SBM. Like in the grower period, these results indicate that feeding diets with greater than 12.4% NDF, or reducing dietary NE by 1% or greater, decreases growth performance of finishing pigs (Graham et al., 2014; Lerner et al., 2020a,b).

A second possible explanation for the reduced growth performance observed by Lerner et al., (2020a,b) and Tolosa et al (2022) when feeding high levels of DDGS could be a result of a branched-chain AA (BCAA) imbalance. Distillers dried grains with solubles are high in Leu in comparison to SBM, which drastically raises the SID Leu:Lys ratio when DDGS are included at 30% of the diet or greater. Excessive levels of Leu have been noted to increase the catabolism of all BCAA, thus reducing feed intake and weight gain when Val and Ile concentrations are not similarly increased (Cemin et al., 2019).

Reducing SBM with a constant level of DDGS.

Adding DDGS at greater than 20 and 30% of the diet results in reduced growth performance in many studies with growing and finishing pigs. However, the variability in SBM level required for optimal growth performance in these studies raises the question, when DDGS are held constant in the diet, what level of SBM optimizes performance? Holen et al. (2022) evaluated the effects of reducing SBM from 16 to 0% in diets containing 25% DDGS while feed-grade Lys, Thr, Trp, Val, and Ile were utilized to maintain SID AA concentrations above NRC (2012) requirement estimates. Reducing SBM tended to decrease G:F; however, there were no observed differences in ADG or ADFI. It should be noted that diet CP concentrations ranged from 19.4 to 13.9% suggesting that SID N content was adequate in all diets to maintain protein synthesis. Faccin et al., (2023) observed a similar response in two experiments in which DDGS were held constant at 10 or 20% of the diet and SBM was reduced to 11.2 and 9.5% of the diet in 39- to 67-kg and 102- to 127-kg pigs, respectively. Apple et al. (2017) observed a linear decrease in growth performance in 62- to 84-kg pigs fed decreasing SBM in corn-based diets with 20% DDGS, despite maintaining consistent SID Lys, Met, Thr, Trp, Ile, and Val concentrations. The greatest reduction was observed when reducing SBM from 5 to 0% of the diet, which corresponded to reducing dietary CP from 14.3 to 12.7%. However, they did not observe the same response in 84- to 100-kg pigs when dietary SBM content was reduced from 6.5 to 0%. Recently, Giacomini et al. (2024) conducted two experiments to determine the effects of reducing SBM in diets containing 30% DDGS, in 32- to 59-kg pigs and in diets containing 15% DDGS in 80- to 134-kg pigs. In the first experiment, it was observed that SBM could be reduced to at least 3.9% (the lowest tested level) of the diet containing 30% DDGS without reducing growth performance of 32 to 59 kg pigs. In 80 to 134 kg pigs, Giacomini et al. (2024) observed that reducing SBM from 6.4 to 0.0% in diets containing 15% DDGS reduced G:F. This reduction appears to be a result of dietary CP falling below 11.8% of the diet. In summary, when reducing SBM in diets containing a set level of DDGS, no negative effects on growth performance have been observed when dietary CP, and therefore N intake, were maintained at levels above that required for adequate protein and NEAA synthesis. Each of these studies maintained DDGS at or below 30%, which has shown little negative impact on growth performance. Therefore, it appears to be possible to maintain growth performance when completely removing SBM from diets containing DDGS (Apple et al., 2017; Holen et al., 2022). These results suggest that SBM is not required to support optimum growth performance when another intact protein source is supplied in adequate concentrations to meet the pig's AA, N, and NE requirement.

Soybean meal net energy content

Discussion of the relative value of SBM would not be complete without discussing the wide range of NE estimates for SBM. In addition to providing AA and biologically active compounds, SBM accounts for a significant portion of the diet's energy content. The NRC (2012) suggests that SBM contains 2,087 kcal/kg of NE, which is 78% the NE value assumed for corn. Recent research has observed that this assumption may underestimate the NE content of SBM. Using indirect calorimetry, Rojas and Stein (2013) compared the NE content of SBM in diets fed to 22 kg pigs and observed that the SBM used contained 2,409 kcal/kg DM, or approximately 103% the NE of corn used. Sotak-Peper et al., (2015) analyzed the metabolizable energy content of 22 SBM samples collected from soybean processing plants from around the United States and used estimated the NE content from ME. On average, SBM contained 2,467 kcal/kg DM, or 92% the NE of corn presented in the NRC (2012). Li et al., (2017) observed that SBM contained 2,709 kcal/kg DM, or 92.4% the NE of corn used in their study. Differences in SBM NE content amongst studies could be due to a variety of factors including SBM source and processing methods.

A different approach to estimate NE of SBM in commercial production has been suggested as a replacement to calorimetry studies which require labor-intensive procedures and specialized equipment (Boyd et al., 2011; Cemin et al., 2020). In this approach, diets containing increasing concentrations of an ingredient (i.e. SBM) are fed, and differences in caloric efficiency (CE) are used to estimate the energy content of the test ingredient relative to corn. Cemin et al. (2020) utilized this method in two experiments to estimate the NE content of SBM with 11 to 22 kg pigs. Through this analysis, they estimated that SBM contains between 2,816 and 3,236 kcal/kg NE, or between 105.4 and 124.7% the NE of corn (NRC, 2012). Kim et al. (2023) recently estimated that SBM contains approximately 94% the NE of corn (NRC, 2012) in 50- to 80-kg pigs and up to 125% the NE of corn in 114 to 138 kg pigs. The use of CE to estimate NE content of an ingredient has its limitations, as this approach assumes that the NE value of the “known” ingredient, corn in these experiments, is applicable (Cemin et al., 2020). The reason for these differences between commercial and university settings is not apparent as there are multiple potentially confounding factors; however, the anti-inflammatory, antioxidant, and anti-viral effects of biologically active compounds (i.e., isoflavones and saponins) may partially explain this response. Increased concentrations of biologically active compounds may allow for the redirection of NE away from an immune response towards protein deposition. As such, this approach may overestimate the true NE of SBM. However, these results suggest that the NRC (2012) underestimates the NE content of SBM, as recent studies estimate an NE value at least 92% of the assumed NE content of corn.

Soybean meal level during periods of heat stress

Feeding pigs in high ambient temperature environments has been observed to reduce ADFI by 8 to 48% (Wolp et al., 2012; de Oliveira et al., 2018), which corresponds with a similar reduction in weight gain. This reduction in feed intake is in attempt to decrease metabolic heat production associated with the digestive process. It has been proposed that reducing dietary CP, via replacement of SBM with feed-grade AAs, reduces the heat increment as digestion of intact protein requires deamination of excess AA and an associated synthesis and excretion of urea (Fuller et al., 1987; Noblet et al., 1987). For each trial evaluating the effects of dietary SBM concentration during a period of heat stress within this review, a summary was compiled similar to Table 1 (Table 3).

Le Bellego et al. (2002) analyzed the effect of reducing SBM from 26.6 to 13.6% in 27- to 65-kg pigs and from 20.8 to 8.2% in 65- to 100-kg pigs, in environments with ambient temperatures set to 22 or 29°C. During the grower phase, there were no observed interactions between ambient temperature and dietary SBM; however, increasing ambient temperature reduced ADFI and ADG by 12.3 and 10.7%, respectively. Soybean meal level did not affect ADG or ADFI during the grower phase. During the finisher phase (65- to 100-kg), there was an interaction between ambient temperature and dietary SBM on ADFI, in which reducing SBM (20.8 to 8.2% of the diet) reduced ADFI in thermoneutral conditions, but there was no effect at high ambient temperatures. Lopez et al. (1994) analyzed the effect of total Lys level, SBM level, and heat stress on growth performance of 70 to 105 kg pigs in a factorial experiment. Reducing

SBM to 1.5 or 16.2% of the diet in diets with 0.6 or 1.0% Total Lys, respectively, had no effect on ADG, ADFI, or G:F, regardless of environmental condition. Kerr et al. (2003) reduced SBM from 20.1 to 11.1% of the diet and observed no effect on growth performance of 23- to 39-kg pigs in an environment held at 33°C. Recently, de Oliveira et al. (2023) reduced SBM (24.9 to 11.7% for 68- to 93-kg pigs and 19.8 to 7.8% for 93- to 113-kg pigs) in two ambient temperatures (22 or 35°C). Diets were formulated such that all EAAs were at or above NRC (2012) requirement estimates. Pigs fed in the high temperature environment had reduced ADFI and ADG by 7.28 and 6.06%, respectively, while G:F improved by 1.62%. However, reducing SBM concentration had no effect on growth performance. In each of these experiments, diets were formulated to be isocaloric, indicating that increasing SBM did not affect growth performance in heat stress environments.

When diurnal ambient temperature ranged from 24.5 to 42.6°C, Morales et al. (2018) studied the effects of decreasing SBM from 30.3 to 4.0%, while maintaining SID EAA concentrations at or above NRC (2012) requirement estimates (wheat-based diets, 30- to 60-kg pigs). Decreasing SBM increased G:F by 8.23%. A subsequent study conducted in an environment with diurnal temperatures between 27.7 and 37.7°C observed that reducing SBM from 20.5 to 10% increased G:F by 8.4%, although this improvement was not statistically significant. The improvements in G:F might be explained by the 2 to 3% increase in NE of the diets as SBM content of the diet decreased.

Conversely, across a two-year period Myer et al. (2008) reduced SBM from 17.8 to 7.8% in growing and finishing pigs in either the summer or fall/winter seasons to simulate a period of heat stress vs a period of thermoneutral temperatures. During the summer, reducing SBM reduced ADG, while there was no difference during the fall/winter. It appears that the reduction in ADG observed when feeding 7.8% SBM during high ambient temperatures may have been due to a borderline deficiency in SID Val, Ile, or N intake/d resulting from the numeric decrease in average daily feed intake that was also observed.

In summary, periods of heat stress adversely affect feed intake, and therefore growth rate, of growing-finishing pigs. Practices to reduce dietary SBM concentration to reduce heat increment during heat stress appear to not be effective. When NE, N, and AA intake are maintained above the pig's requirements, SBM level does not appear to affect growth performance during periods of heat stress.

Soybean meal level during a disease challenge

Porcine reproductive and respiratory syndrome virus (PRRSV), as well as other respiratory pathogens, are leading health concerns in swine production. Therefore, vaccination protocols, management strategies, and nutritional interventions are of high interest to ameliorate the effects of these pathogens. Feeding increased levels of SBM is one such nutritional strategy that has been observed to potentially recover a portion of this lost performance.

The first experiment known to show the implications on growth performance of increasing dietary SBM concentration during high immune challenge was conducted by Boyd et al. (2010), where they observed that during a PRRSV, porcine circovirus, and *Streptococcus suis* challenge, decreasing SBM from 25.3 to 17.0% of the diet decreased ADG and G:F by 9.7 and 8.3%, respectively. This response may be a result of biologically active compounds present in SBM (i.e., isoflavones and saponins), or increased SID N resulting from the high SBM inclusion. Rochell et al. (2015) conducted a study in 7- to 18-kg pigs to examine the interactive effects of a PRRSV infection and SBM level (17.5 vs. 29% of the diet) on growth performance and immune response. In this experiment, PRRSV infection resulted in a 42, 30, and 18% reduction in ADG, ADFI, and G:F, respectively, In PRRSV infected pigs, it was observed that increasing SBM to 29% of the diet resulted in a 19 and 13% improvement in ADG and G:F, respectively, compared to those pigs fed a diet with 17.5% SBM. Additionally, in PRRSV-infected pigs, increasing SBM reduced serum tumor necrosis factor α concentrations and serum viral load at 14 d post infection (dpi). These results suggest that increasing SBM levels reduced immune activation, therefore partially ameliorating the negative effect of a PRRSV infection on growth performance. Like Boyd et al. (2010), results from Rochell et al. (2015) support the hypothesis that increasing SBM improves performance of PRRSV infected pigs; however, it remained unclear whether this was a result of increased nutrient intake or bioactive compound content.

It has been noted that activation of the immune system may increase the demand for specific AAs to produce immune-specific molecules (Klasing, 1988; Reeds et al., 1994). Schweer et al. (2018) increased SBM from 10.0 to 29.7% of the diet fed to pigs with or without a PRRSV inoculation and observed no interactions between PRRSV infection and dietary SBM content on SID of N or AAs. However, PRRSV infection resulted in a reduction in basal endogenous loss of Arg, Ala, and Pro, which may indicate their importance in the production of immune-specific molecules within the body. The lack of PRRSV × dietary SBM interactions suggests that PRRSV does not differentially affect digestibility of AAs, thus reinforcing the hypothesis that biologically active compounds in SBM may be responsible for the improved performance during PRRSV infection.

Enteric diseases, such as F18+ *Escherichia coli* infection, are another prominent health concern in the swine industry. It could be hypothesized that biologically active compounds in SBM may help partially ameliorate these negative effects. Recent work by Deng et al. (2024) studied the effects of increasing SBM during an *E. coli* challenge in newly weaned pigs. In this experiment, pigs were fed diets containing 12 or 24% SBM from d 0 to 11 post-weaning and 14 or 26% SBM from d 11 to 25. They observed that increasing SBM increased ADFI, ADG, and BW of pigs experimentally infected with *E. coli*. Additionally, it was observed that increasing SBM reduced the concentration of the pro-inflammatory cytokines, tumor necrosis factor-alpha and interleukin 1β, in jejunal samples. These results suggest that increasing SBM may decrease the inflammatory response during an enteric disease challenge, thus allowing pigs to maintain feed intake and growth performance.

Isoflavones are flavonoid compounds found in SBM that possess anti-inflammatory and antioxidative properties (Smith and Dilger, 2018). Smith et al. (2020) studied the effect of PRRSV inoculation and dietary isoflavone concentration in pigs from weaning to market weight. In this experiment, diets were formulated with 0 or 4.5% of an isoflavone mixture product, such that the diet containing isoflavones had approximately equal isoflavones to a corn-SBM diet with 20% SBM. Pigs in this study were unintentionally exposed to a secondary bacterial infection of *Streptococcus suis.* Porcine Reproductive and Respiratory Syndrome Virus reduced ADG and ADFI during the first 34 dpi (during the active infection period) and BW throughout the 161-d study compared to non-challenged control pigs. From 0 to 34 dpi, feeding isoflavones did not affect growth performance; however, there was a positive effect on immune response criteria. For example, all serum samples collected from pigs fed isoflavones on 34 dpi contained anti-PRRSV neutralizing antibody titer levels above the established level of protection (≥ 1:8), which may help explain the mortality response observed in this trial. While there were no statistical differences, they observed a 47% mortality rate in PRRSV-infected pigs fed diets without isoflavones; however, this rate was reduced to 25% in pigs fed isoflavone-containing diets. This would suggest that circulating levels of serum isoflavones allowed pigs to better mount an appropriate immune response in the face of multiple pathogens. This reduction in mortality in pigs fed diets containing isoflavones could yield benefits in commercial pork production in the face of numerous immune challenges (Smith et al., 2020). Thus, further research into the mechanism by which SBM, and its' anti-inflammatory and anti-viral compounds (i.e., isoflavones and saponins), affect the immune response of pigs is of utmost importance in the face of recent high rates of infection-based mortality.

Conclusion

Based on this review, it appears that reducing dietary SBM below 10.0% and 8.8% in 20- to 85-kg pigs and greater than 100-kg pigs, respectively, reduces growth performance in low protein-amino acid fortified diets where SBM is the only intact protein source. These same inclusion levels should be maintained during heat stress, as the available data shows no benefit to further reducing SBM. Including greater than 20 and 30% DDGS in growing and finishing pig diets, respectively, in replacement of SBM, reduces growth performance. However, when NE, EAA's, and N are provided in adequate levels and DDGS are not fed in excess, it appears that SBM can be removed from the diet without reducing growth performance. During diseases challenges, the limited available data suggests that increasing dietary SBM may improve immune response and growth performance, but there is not enough available data to determine the concentration required to elicit these improvements. Thus, a deeper understanding of SBM's immuno-supportive functions important is an important research focus in the face of current disease pressure.

References

Apple, J. K., C. V. Maxwell, B. E. Bass, J. W. S. Yancey, R. L. Payne, and J. Thomson. 2017. Effects of reducing dietary crude protein levels and replacement with crystalline amino acids on growth performance, carcass composition, and fresh pork quality of finishing pigs fed ractopamine hydrochloride. J. Anim. Sci. 95:4971–4985. doi:10.2527/jas2017.1818.

Boyd, R. D., M. E. Johnston, and C. E. Zier-Rush. 2010. Soybean meal level modulates the adverse effect of high immune stress and feed efficiency in growing pigs. *Proc. MN Nutr. Conf.* 71:167-174 [accessed March 9, 2023]. https://conservancy.umn.edu/bitstream/handle/11299/204236/SF95_M658a-71-2010_magr56244.pdf?sequence=1.

Boyd, R. D., C. E. Zier-Rush, and C. E. Fralick. 2011. Practical method for estimating productive energy (NEm+g) estimation of soybean meal for growing pigs. J. Anim. Sci. 2011; 89(E-Suppl. 2):89. (Abstr.).

Castell, A. G. 1976. Comparison of faba beans (Vicia faba) with soybean meal or field peas (Pisum sativum) as protein supplements in barley diets for growing-finishing pigs. Can. J. Anim. Sci. 56:425-432. doi:10.4141/cjas76-053.

Cemin, H. S., M. D. Tokach, J. C. Woodworth, S. S. Dritz, J. M. DeRouchey, and R. D. Goodband. 2019. Branched-chain amino acid interactions in growing pig diets. Transl. Anim. Sci. 3:1246-1253. doi:10.1093/tas/txz087.

Cemin, H. S., H. E. Williams, M. D. Tokach, S. S. Dritz, J. C. Woodworth, J. M. DeRouchey, R. D. Goodband, K. F. Coble, B. A. Carrender, and M. J. Gerhart. 2020. Estimate of the energy value of soybean meal relative to corn based on growth performance of nursery pigs. J. Anim. Sci. Biotechnol. 11:70. doi:10.1186/s40104-020-00474-x.

Cromwell, G. L., M. J. Azain, O. Adeola, S. K. Baidoo, S. D. Carter, T. D. Crenshaw, S. W. Kim, D. C. Mahan, P. S. Miller, and M. C. Shannon. 2011. Corn distillers dried grains with solubles in diets for growing-finishing pigs: A cooperative study. J. Anim. Sci. 89:2801–2811. doi:10.2527/jas.2010-3704.

De la Llata, M., S. S. Dritz, M. D. Tokach, R. D. Goodband, and J. L. Nelssen. 2002. Effects of increasing L-lysine HCl in corn- or sorghum-soybean meal-based diets on growth performance and carcass characteristics of growing-finishing pigs. J. Anim. Sci. 80:2420–2432. doi:10.1093/ansci/80.9.2420.

Deng, Z., H. Choi, and S. W. Kim. 2024. Impacts of replacing soybean meal with processed soybean meal on intestinal health and growth of nursery pigs challenged with F18+ Escherichia coli. Anim. Biosci. doi:10.5713/ab.24.0566.

de Oliveira, R. F., R. H. R. Moreira, M. L. T. Abreu, M. P. Gionbelli, A. O. Texeira, V. S. Cantarelli, and R. A. Ferreira. 2018. Effects of air temperature on physiology and productive performance of pigs during growing and finishing phases. S. Afr. J. Anim. Sci. 48:627-635. doi:10.4314/sajas.v48i4.4.

de Oliveira, M. J. K., A. D. B. Melo, D. A. Marçal, G. A. da Cunha Valini, C. A. Silva, A. M. Veira, A. Z. Fraga, P. R. Arnaut, P. H. R. F. Campos, L. S. dos Santos, J. K. K. Htoo, H. G. Brand, and L. Hauschild. 2023. Effects of lowering dietary protein content without or with increased protein-bound and feed-grade amino acids supply on growth performance, body composition, metabolism, and acute-phase protein of finishing pigs under daily cyclic heat stress. J. Anim. Sci. 101:1-16. doi:10.1093/jas/skac387.

Duarte, M. E., W. Parnsen, S. Zhang, M. L. T. Abreu, and S. W. Kim. 2024. Low crude protein formulation with supplemental amino acids for its impacts on intestinal health and growth performance of growing-finishing pigs. J. Anim. Sci. Biotechnol. 15:55. doi:10.1186/s40104-024-01015-6.

Faccin, J. E. G., M. D. Tokach, J. M. DeRouchey, J. T. Gebhardt, R. D. Goodband, and J. C. Woodworth. 2023. Effects of increasing soybean meal levels on growth performance and carcass characteristics of pigs in grower and late-finishing phases. Kansas Agricultural Experiment Station Research Reports. 9:7. doi:10.4148/2378-5977.8522.

Figueroa, J. L., A. J. Lewis, P. S. Miller, R. L. Fischer, R. S. Gómez, and R. M. Diedrichsen. 2002. Nitrogen metabolism and growth performance of gilts fed standard corn-soybean meal diets or low-crude protein, amino acid-supplemented diets. J. Anim. Sci. 80:2911–2919. doi:10.2527/2002.80112911x.

Fuller, M. F., P. J. Reeds, A. Cadenhead, B. Seve, and T. Preston. 1987. Effects of the amount and quality of dietary protein on nitrogen metabolism and protein turnover of pigs. Br. J. Nutr. 58:287-300. doi:10.1079/BJN19870096

Giacomini, P., M. D. Tokach, J. M. DeRouchey, J. T. Gebhardt, R. D. Goodband, K. N. Gaffield, J. C. Woodworth, A. L. Petry, M. Putnam, A. Gaines, R. D. Boyd, C. Shull, and O. Mendoza. 2024. Effects of increasing soybean meal levels in diets with or without distillers dried grains with solubles on growth performance and carcass characteristics of pigs in early and late-finishing phases. *(in press)*

Gómez, R. S., A. J. Lewis, P. S. Miller, and H. Y. Chen. 2002. Growth performance, diet apparent digestibility, and plasma metabolite concentrations of barrows fed corn-soybean meal diets or low-protein, amino acid-supplemented diets at different feeding level. J. Anim. Sci. 80:644-653. doi:10.2527/2002.80112911x.

Graham, A. B., R. D. Goodband, M. D. Tokach, S. S. Dritz, J. M. DeRouchey, and S. Nitikanchana, 2014. The effect of medium-oil dried distillers grains with solubles on growth performance, carcass traits, and nutrient digestibility in growing-finishing pigs. J. Anim. Sci. 92:604-611. doi:10.2527/jas2013-6798.

He, Z., X. Zhan, S. Cao, X. Wen, L. Hou, S. Liu, H. Zheng, K. Gao, X. Yang, Z. Jiang, and L. Wang. 2023. Effect of miscellaneous meal replacements for soybean meal on growth performance, serum biochemical parameters, and gut microbiota of 50-75 kg growing pigs. Animals. 13:3499. doi:10.3390/ani13223499.

Hilbrands, A. M., L. J. Johnston, R. B. Cox, F. Forcella, R. Gesch, and Y. Z. Li. 2021. Effects of increasing dietary inclusion of camelina cake on growth performance of growing-finishing pigs. Transl. Anim. Sci. 5:1-10. doi:10.1093/tas/txab140.

Holen, J. P., R. D. Goodband, M. D. Tokach, J. C. Woodworth, J. M. DeRouchey, and J. T. Gebhardt. 2022. Effects of increasing soybean meal in corn-based diets on the growth performance of late finishing pigs. Transl. Anim. Sci. 7:1-8. doi:10.1093/tas/txac165.

Kerr, B. J., F. K. McKeith, and R. A. Easter. 1995. Effect on performance and carcass characteristics of nursery to finisher pigs fed reduced crude protein, amino acid-supplemented diets. J. Anim. Sci. 73:433–440. doi:10.2527/1995.732433x.

Kerr, B. J., J. T. Yen, J. A. Nienaber, and R. A. Easter. 2003. Influences of dietary protein level, amino acid supplementation and environmental temperature on performance, body composition, organ weights and total heat production of growing pigs. J. Anim. Sci. 81:1998–2007. doi:10.2527/2003.8181998x

Kim, T. H., J. E. G. Faccin, R. D. Goodband, M. D. Tokach, J. M. DeRouchey, J. C. Woodworth, and J. T. Gebhardt. 2023. Effects of increasing energy or lysine in soybean meal-based diets on early and late finishing pig performance. Kansas Agricultural Experiment Station Research Reports. 9:7. doi:10.4148/2378-5977.8527.

Klasing, K. C. 1988. Nutritional aspects of leukocytic cytokines. J. Nutr. 118:1436-1446. doi:10.1093/jn/118.12.1436.

Knowles, T. A., L. L. Southern, T. D. Bidner, B. J. Kerr, and K. G. Friesen. 1998. Effect of dietary fiber or fat in low-crude protein, crystalline amino acid-supplemented diets for finishing pigs. J. Anim. Sci. 76:2818. doi:10.2527/1998.76112818x.

Lazaga, R., K. N. Gaffield, M. S. Spinler, R. D. Goodband, J. T. Gebhardt, M. D. Tokach, J. M. DeRouchey, and J. C. Woodworth. 2024a. Effect of increasing 6% oil corn dried distillers grains with solubles on finishing pigs growth performance, carcass characteristics, and diet economics. *(in press)*

Lazaga, R., H. M. Cordoba, K. N. Gaffield, R. D. Goodband, J. T. Gebhardt, M. D. Tokach, J. M. DeRouchey, and J. C. Woodworth. 2024b. Effect of increasing 3% oil corn dried distillers grains with solubles on nursery and finishing pig growth performance, carcass characteristics, and diet economics. *(in press)*

Le Bellego, L., J. van Milgen, and J. Noblet. 2002. Effect of high temperature and low-protein diets on the performance of growing-finishing pigs. J. Anim. Sci. 80:691–701. doi:10.2527/2002.803691x.

Lee, J. H., J. H. Kim, J. D. Kim, S. W. Kim, and I. K. Han. 2001. Effects of low crude protein diets supplemented with synthetic amino acids on performance, nutrient utilization and carcass characteristics in finishing pigs reared using a phase feeding regimen. Asian-Aust. J. Anim. Sci. 14:655-667.

Lerner, A. B., M. D. Tokach, J. M. DeRouchey, S. S. Dritz, R. D. Goodband, J. C. Woodworth, and M. Allerson. 2020a. Effects of switching from corn distillers dried grains with solubles- to corn- and soybean meal-based diets on finishing pig performance, carcass characteristics, and carcass fatty acid composition. Transl. Anim. Sci. 4:715–723. doi:10.1093/tas/txaa070.

Lerner, A. B., M. D. Tokach, J. M. DeRouchey, S. S. Dritz, R. D. Goodband, J. C. Woodworth, C. W. Hastad, K. F. Coble, E. Arkfeld, H. C. Cartagena, and C. Vahl. 2020b. Effects of corn distillers dried grains with solubles in finishing diets on pig growth performance and carcass yield with two different marketing strategies. Transl. Anim. Sci. 4:737–749. doi:10.1093/tas/txaa071.

Li, Z., Y. Li, Z. Lv, H. Liu, J. Zhao, J. Noblet, F. Wang, C. Lai, D. Li. 2017. Net energy of corn, soybean meal and rapeseed meal in growing pigs. J. Anim. Sci. Biotechnol. 8:44. doi:10.1186/s40104-017-0169-1

Linneen, S. K., J. M. DeRouchey, S. S. Dritz, R. D. Goodband, M. D. Tokach, and J. L. Nelssen. 2008. Effects of dried distillers grains with solubles on growing and finishing pig performance in a commercial environment. J. Anim. Sci. 86:1579–1587. doi:10.2527/jas.2007-0486.

Little, K. L., B. M. Bohrer, T. Maison, Y. Liu, H. H. Stein, and D. D. Boler. 2015. Effects of feeding canola meal from high-protein or conventional varieties of canola seeds on growth performance, carcass characteristics, and cutability of pigs. J. Anim. Sci. 93:1284-1297. doi:10.2527/jas.2014-8359.

Liu, S., J. Xie, Z. Fan, X. Ma, and Y. Yin. 2023. Effects of low protein diet with a balanced amino acid pattern on growth performance, meat quality and cecal microflora of finishing pigs. J. Sci. Food Agric. 103:957–967. doi:10.1002/jsfa.12245.

Lopez, J., R. D. Goodband, G. L. Allee, G. W. Jesse, J. L. Nelssen, M. D. Tokach, D. Spiers, and B. A. Becker. 1994. The effects of diets formulated on an ideal protein basis on growth performance, carcass characteristics, and thermal balance of finishing gilts housed in a hot, diurnal environment. J. Anim. Sci. 72:367-379. doi:10.2527/1994.722367x.

Morales, A., L. Buenabad, G. Castillo, N. Arce, B. A. Araiza, J. K. Htoo, and M. Cervantes. 2015. Low-protein amino acid–supplemented diets for growing pigs: Effect on expression of amino acid transporters, serum concentration, performance, and carcass composition. J. Anim. Sci. 93:2154–2164. doi:10.2527/jas.2014-8834.

Morales, A., M. Chávez, N. Vásquez, J. K. Htoo, L. Buenabad, S. Espinoza, and M. Cervantes. 2018. Increased dietary protein or free amino acids supply for heat stress pigs: effect on performance and carcass traits. J. Anim. Sci. 96:1419–1429. doi:10.1093/jas/sky044.

Noblet, J., Y. Henry, and S. Dubois. 1987. Effect of protein and lysine levels in the diet on body gain composition and energy utilization in growing pigs. J. Anim. Sci. 65:717-726 doi:10.2527/jas1987.653717x

NRC. 1998. Nutrient requirements of swine. 10th ed. Natl. Acad. Press, Washington, DC.

NRC. 2012. Nutrient requirements of swine: 11th ed. Natl. Acad. Press, Washington, DC.

Omoni, A. O., and R. E. Aluko. 2005. Soybean Foods and Their Benefits: Potential Mechanisms of Action. Nutrition Reviews. 63:272–283. doi:10.1111/j.1753-4887.2005.tb00141.x.

Reeb, M. E., J. C. Woodworth, J. M. DeRouchey, M. D. Tokach, R. D. Goodband, and J. T. Gebhardt. 2023. Evaluating the effects of soybean meal levels and valine, isoleucine, and tryptophan adjustment in diets with or without dried distillers grain solubles on finishing pig performance and carcass characteristics. Kansas Agricultural Experiment Station Research Reports. 9:7. doi:10.4148/2378-5977.8526.

Reeds, P. J., C. R. Fjeld, and F. Jahoor. 1994. Do the differences between the amino acid compositions of acute-phase and muscle proteins have a bearing on nitrogen loss in traumatic stress? J. Nutr. 124:906-910.

Rochell, S. J., L. S. Alexander, G. C. Rocha, W. G. Van Alstine, R. D. Boyd, J. E. Pettigrew, and R. N. Dilger. 2015. Effects of dietary soybean meal concentration on growth and immune response of pigs infected with porcine reproductive and respiratory syndrome virus. J. Anim. Sci. 93:2987–2997. doi:10.2527/jas.2014-8462.

Rojas, O. J., and H. H. Stein. 2013. Concentration of digestible, metabolizable, and net energy and digestibility of energy and nutrients in fermented soybean meal, conventional soybean meal, and fish meal fed to weanling pigs. J. Anim. Sci. 91:4397-4405.

doi:10.2527/jas2013-6409.

Royall, R. Q., R. D. Goodband, M. D. Tokach, J. M. DeRouchey, J. C. Woodworth, and J. T. Gebhardt. 2022. Effects of adding potassium bicarbonate to diets with high or low crystalline lysine to influence dietary cation–anion difference on finishing pig growth performance. Transl. Anim. Sci. 6:1-6. doi:10.1093/tas/txac107.

Schweer, W. P., J. F. Patience, E. R. Burrough, B. J. Kerr, and N. K. Gabler. 2018. Impact of PRRSV infection and dietary soybean meal on ileal amino acid digestibility and endogenous amino acid losses in growing pigs1. J. Anim. Sci. 96:1846–1859. doi:10.1093/jas/sky093.

Smith, B. N., and R. N. Dilger. 2018. Immunomodulatory potential of dietary soybean-derived isoflavones and saponins in pigs. J. Anim. Sci. 96:1288–1304. doi:10.1093/jas/sky036.

Smith, B. N., M. L. Oelschlager, M. S. A. Rasheed, and R. N. Dilger. 2020. Dietary soy isoflavones reduce pathogen-related mortality in growing pigs under porcine reproductive and respiratory syndrome viral challenge. J. Anim. Sci. 98:1-15. doi:10.1093/jas/skaa024.

Smith, L. A., J. G. M. Houdijk, D. Homer, and I. Kyriazakis. 2013. Effects of dietary inclusion of pea and faba bean as a replacement for soybean meal on grower and finisher pig performance and carcass quality. J. Anim. Sci. 91:3733–3741. doi:10.2527/jas.2012-6157.

Sotak-Peper, K. M., J. C. Gonzalez-Vega, and H. H. Stein. 2015. Concentrations of digestible, metabolizable, and net energy in soybean meal produced in different areas of the United States and fed to pigs. J. Anim. Sci. 93:5694-5701. doi:10.2527/jas2015-9281.

Soto, J. A., M. D. Tokach, S. S. Dritz, J. C. Woodworth, J. M. DeRouchey, R. D. Goodband, and F. Wu. 2019. Optimal dietary standardized ileal digestible lysine and crude protein concentration for growth and carcass performance in finishing pigs weighing greater than 100 kg. J. Anim. Sci. 97:1701–1711. doi:10.1093/jas/skz052.

Soy Stats. 2022. International: World Protein Meal Consumption. [accessed May 5, 2023]. http://soystats.com/international-world-protein-meal-consumption/

Stein, H. H., L. L. Berger, J. K. Drackley, G. C. Fahey, Jr., D. C. Hernot, and C. M. Parsons. 2008. Nutritional properties and feeding values of soybeans and their coproducts. In: L. A. Johnson, P. J. White, and R. G. Galloway, editors, Soybeans: Chemistry, production, processing, and utilization. AOCS Press, Urbana, IL. p. 613-660.

Stein, H. H., and G. C. Shurson. 2009. Board-invited review: The use and application of distillers dried grains with solubles in swine diets. J. Anim. Sci. 87:1292-1303. doi:10.2527/jas.2008-1290.

Stein, H. H, J. A. Ibagon, and M. Cristobal. 2024. Soybean meal or crystalline amino acids in diets for growing pigs: impact on diet net energy, pig growth performance, and nitrogen retention. 23rd Midwest Swine Nutrition Conference Proceedings. 45-51.

Tokach, M. D., R. G. Main, S. S. Dritz, J. M. DeRouchey, R. D. Goodband, J. L. Nelssen, and J. L. Usry. 2003. Effects of increasing crystalline lysine and dietary fat on finishing pig growth performance. Kansas State University Swine Day Report 2003.

Tolosa, A. F., M. D. Tokach, R. D. Goodband, J. C. Woodworth, J. M. DeRouchey, and J. T. Gebhardt. 2022. Evaluation of increasing digestible threonine to lysine ratio in corn–

soybean meal diets without and with distillers dried grains with solubles on growth performance of growing-finishing pigs. Transl. Anim. Sci. 6:1-6. doi:10.1093/tas/txac058.

Tuitoek, K., L. G. Young, C. F. M. de Lange, and B. J. Kerr. 1997. The effect of reducing excess dietary amino acids on growing-finishing pig performance: an evaluation of the ideal protein concept. J. Anim. Sci. 75:1575-1583. doi:10.2527/1997.7561575x.

Widmer, M. R., L. M. McGinnis, D. M. Wulf, and H. H. Stein. 2008. Effects of feeding distillers dried grains with solubles, high-protein distillers dried grains, and corn germ to growing-finishing pigs on pig performance, carcass quality, and the palatability of pork. J. Anim. Sci. 86:1819–1831. doi:10.2527/jas.2007-0594.

White, H. M., B. T. Richert, J. S. Radcliffe, A. P. Schinckel, J. R. Burgess, S. L. Koser, S. S. Donkin, and M. A. Latour. 2009. Feeding conjugated linoleic acid partially recovers carcass quality in pigs fed dried corn distillers grains with solubles. J. Anim. Sci. 87:157-166. doi:10.2527/jas.2007-0734

Wolp, R. C., N. E. B. Rodrigues, M. G. Zangeronimo, V. S. Cantarelli, E. T. Fialho, R. Philomeno, R. R. Alvarenga, and L. F. Rocha. 2012. Soybean oil and crude protein levels for growing pigs kept under heat stress conditions. Livest. Sci. 147:148–153. doi:10.1016/j.livsci.2012.04.014.

Yun, H. M., X. J. Lei, S. I. Lee, and I. H. Kim. 2018. Rapeseed meal and canola meal can partially replace soybean meal as a protein source in finishing pigs. J. Appl. Anim. Res. 46:195–199. doi:10.1080/09712119.2017.1284076.

Zhan, X., L. Hou, Z. He, S. Cao, X. Wen, S. Liu, Y. Li, S. Chen, H. Zheng, D. Deng, K. Gao, X. Yang, Z. Jiang, and L. Wang. 2024. Effect of miscellaneous meals replacing soybean meal in feed on growth performance, serum biochemical parameters, and microbiota composition of 25-50 kg growing pigs. Animals. 14:1354. doi:10.3390/ani14091354.

Table 3.1. Summary of the optimal soybean meal (SBM) level in feed-grade amino acid (AA)-supplemented diets

					Minimum SBM level to support:		
Item	Major ingredients	BW Range, kg	SBM range, %	CP range, %	ADG[1]	G:F[2]	First limiting nutrient[3]
Grower period							
No response							
Kerr et al., 1995	Corn-SBM	21-55	10.8-21.0	12.0-16.0	NS[4]	NS[4]	N/A[4]
Tuitoek et al., 1997	Corn-SBM	20-55	10.0-19.6	13.0-16.6	NS	NS	N/A
Lee et al., 2001	Corn-SBM	55-72	13.4-22.6	13.0-16.0	NS	NS	N/A
Morales et al., 2015	Wheat-SBM	24-40	4.0-30.3	14.0-22.0	NS	NS	N/A
Royall et al., 2022	Corn-SBM	35-85	21.5-28.5	17.1-19.5	NS	NS	N/A
Duarte et al., 2024	Corn-SBM	20-40	19.0-25.0	16.0-18.0	NS	NS	N/A
Stein et al., 2024	Corn-SBM	32-61	18.8-34.5	13.4-20.0	NS	NS	N/A
Limiting AA							
De la Llata et al., 2002	Sorghum-SBM	56-80	8.5-17.1	11.2-14.4	12.9	12.9	Thr
De la Llata et al., 2002	Corn-SBM	63-80	8.0-16.5	11.2-14.4	12.3	12.3	Thr
Figueroa et al., 2002	Corn-SBM	20-50	5.6-20.3	10.1-16.3	11.5	8.4	Val
Gómez et al., 2002	Corn-SBM	31-54	10.1-21.0	12.0-16.2	21.0	21.0	Val
Gómez et al., 2002	Corn-SBM	54-84	4.7-15.5	10.2-14.2	15.5	15.5	Val
Gómez et al., 2002	Corn-SBM	32-58	10.1-21.0	11.7-15.9	21.0	21.0	Val
Giacomini et al., 2024	Corn-SBM	32-59	17.5-34.9	14.7-20.7	NS	23.3	His
Non-AA response							
Faccin et al., 2023	Corn-SBM	43-72	19.1-33.5	16.3-21.3	22.6	22.6	Unknown
Duarte et al., 2024	Corn-SBM	34-55	8.9-21.2	12.6-16.7	NS	15.6	Unknown
Early finisher period							
No growth response							
Kerr et al., 1995[5]	Corn-SBM	55-90	8.1-15.7	11.0-14.0	NS	NS	N/A
Tokach et al., 2003	Corn-SBM	71-90	15.5-22.6	13.9-16.6	NS	NS	N/A
Kim et al., 2023	Corn-SBM	50-80	19.1-33.4	16.3-21.3	NS	NS	N/A
Liu et al., 2023	Corn-SBM	70-105	0.0-16.6	8.1-13.6	NS	NS	N/A
Duarte et al., 2024	Corn-SBM	54-79	10.9-18.8	13.0-15.6	NS	NS	N/A
Limiting AA							
Tuitoek et al.,1997	Corn-SBM	55-100	5.1-14.7	11.0-14.2	9.9	9.9	His/N
Lee et al., 2001	Corn-SBM	72-90	8.0-17.2	11.0-14.0	14.3	14.3	N
Lee et al., 2001[6]	Corn-SBM	90-105	2.9-11.8	9.0-12.0	NS	NS	N
Duarte et al., 2024	Corn-SBM	79-99	6.8-14.4	11.4-13.9	14.4	NS	N
Late finisher period							
No response							
Royall et al., 2022	Corn-SBM	85-130	13.2-20.6	13.8-16.3	NS	NS	N/A
Faccin et al., 2023	Corn-SBM	102-130	11.2-23.2	13.1-17.3	NS	NS	N/A
Kim et al., 2023	Corn-SBM	114-138	11.2-23.2	12.7-15.3	NS	NS	N/A
Duarte et al., 2024	Corn-SBM	99-123	3.0-7.6	9.9-11.3	NS	NS	N/A

Limiting AA							
De la Llata et al., 2002	Sorghum-SBM	80-114	3.3-11.8	9.1-12.4	7.5	7.5	Thr
De la Llata et al., 2002	Corn-SBM	80-109	2.6-11.1	9.1-12.4	11.1	11.1	Thr
Limiting N intake							
Knowles et al., 1998	Corn-SBM	102-111	10.7-20.1	11.7-15.5	NS	20.1	N
Soto et al., 2019[7]	Corn-SBM	110-128	3.0-12.3	9.0-13.1	9.2	9.2	N
Soto et al., 2019	Corn-SBM	112-135	0.5-13.6	8.9-12.9	10.3	10.3	N
Holen et al., 2022	Corn-SBM	105-127	5.0-20.0	11.0-14.1	8.8	8.8	N
Giacomini et al., 2024	Corn-SBM	80-134	6.5-21.3	10.3-15.4	NS	16.4	N

---

[1] Increasing SBM concentration beyond this level resulted in no further improvement in ADG within each individual trial.

[2] Increasing SBM concentration beyond this level resulted in no further improvement in G:F within each individual trial.

[3] Reducing SBM below the minimum level to support growth performance resulted in the nutrient listed being deficient based on NRC (1998; 2012) requirement estimates.

[4] NS; no statistical difference observed between dietary treatments. N/A; based on the statistical response, no nutrients were present in a deficient quantity.

[5] The dietary treatment containing 15.7% SBM reduced 10th rib BF depth.

[6] The dietary treatments containing 9.0% SBM, or greater, increased carcass yield.

[7] The dietary treatments containing 9.2% SBM, or greater, increased hot carcass weight.

Table 3.2. Summary of the optimal SBM level in diets containing multiple protein sources

Item	Major ingredients	Alternative protein source	BW Range, kg	SBM Range, %	CP Range, %	Minimum SBM level to support: ADG[1]	G:F[2]	Limiting factor[3]
Oilseed by-products and legumes								
Oilseed by-products								
Little et al., 2015	Corn-SBM	High Protein Canola Meal	27-57	0.0-27.0	18.6-20.6	NS[4]	NS	N/A[4]
Little et al., 2015	Corn-SBM	High Protein Canola Meal	57-87	0.0-21.0	15.3-17.4	NS	NS	N/A
Little et al., 2015	Corn-SBM	High Protein Canola Meal	87-115	0.0-18.0	15.2-17.1	NS	NS	N/A
Little et al., 2015	Corn-SBM	Conventional Canola Meal	27-57	0.0-27.0	19.1-20.2	NS	NS	N/A
Little et al., 2015	Corn-SBM	Conventional Canola Meal	57-87	0.0-21.0	15.6-16.8	NS	21.0	NE[5]
Little et al., 2015	Corn-SBM	Conventional Canola Meal	87-115	0.0-18.0	15.7-17.1	18.0	NS	NE
Yun et al., 2018	Corn-SBM	Canola Meal	50-117	18.0-22.0	16.0-16.0	NS	NS	N/A
Hilbrands et al., 2021	Corn-SBM	Camelina Meal	35-127	21.6-26.4	18.0-19.9	26.4	26.4	Anti-nutritional factors/NE
He et al., 2023	Corn-SBM	Rapeseed Meal Cottonseed Meal Sunflower seed Meal	51-78	0.0-21.0	14.7-15.3	NS	NS	N/A
Zhan et al., 2024	Corn-SBM	Rapeseed Meal Cottonseed Meal Sunflower seed Meal	25-50	0.0-22.1	16.0-16.0	0.0	NS	Unknown
Legumes								
Smith et al., 2013	Wheat-Barley-SBM-Canola Meal	Peas	30-60	0.0-14.0	14.1-16.1	NS	NS	N/A
Smith et al., 2013	Wheat-Barley-SBM-Canola Meal	Peas	60-100	0.0-12.0	12.7-13.4	12.0	NS	Unknown
Smith et al., 2013	Wheat-Barley-SBM-Canola Meal	Faba Beans	30-60	0.0-14.0	15.9-16.6	NS	NS	N/A
Smith et al., 2013	Wheat-Barley-SBM-Canola Meal	Faba Beans	60-100	0.0-12.0	15.7-16.0	12.0	12.0	Unknown
Corn dried distillers grains with solubles								
Grower period								
No response								

Widmer et al., 2008	Corn-SBM	DDGS	22-62	19.3-28.5	17.2-17.9	NS	NS	N/A
Linneen et al., 2008	Corn-SBM	DDGS	48-74	25.1-27.0	18.3-20.5	NS	NS	N/A
NDF/NE response								
Linneen et al., 2008	Corn-SBM	DDGS	46-95	22.3-24.3	17.2-22.2	23.6	NS	NDF[6]
Cromwell et al., 2011	Corn-SBM	DDGS	32-60	12.0-25.2	17.5-21.5	20.8	NS	NDF
Tolosa et al., 2022	Corn-SBM	DDGS	35-85	4.2-21.6	17.0-18.3	21.6	21.6	NDF/NE[7]
Reeb et al., 2023	Corn-SBM	DDGS	23-45	23.4-35.3	21.7-21.9	35.3	35.3	NDF
Reeb et al., 2023	Corn-SBM	DDGS	45-73	17.9-26.7	20.8-21.7	26.7	26.7	NDF
Lazaga et al., 2024a	Corn-SBM	DDGS	24-49	17.4-26.3	18.9-21.4	26.3	26.3	NDF
Lazaga et al., 2024a	Corn-SBM	DDGS	49-76	10.6-19.2	16.1-18.7	19.2	19.2	NDF
Lazaga et al., 2024b	Corn-SBM	DDGS	41-60	15.9-25.5	18.6-20.9	25.5	25.5	NDF
Finishing period								
No growth response								
Widmer et al., 2008	Corn-SBM	DDGS	62-104	12.8-21.6	14.8-16.4	NS	NS	N/A
Widmer et al., 2008	Corn-SBM	DDGS	104-128	5.9-15.1	11.7-12.6	NS	NS	N/A
White et al., 2009	Corn-SBM	DDGS	88-111	10.9-14.3	12.5-19.6	NS	NS	N/A
Cromwell et al., 2011	Corn-SBM	DDGS	60-91	6.0-19.8	15.9-19.0	NS	NS	N/A
Reeb et al., 2023	Corn-SBM	DDGS	73-100	11.7-20.9	16.1-19.2	NS	NS	N/A
Reeb et al., 2023	Corn-SBM	DDGS	100-137	10.5-19.6	12.5-15.4	NS	NS	N/A
NDF/NE response								
Cromwell et al., 2011[8]	Corn-SBM	DDGS	91-120	2.0-15.0	14.2-17.4	NS	NS	NDF
Graham et al., 2014[9]	Corn-SBM	DDGS	69-128	8.7-16.7	15.2-19.0	16.7	16.7	NDF
Lerner et al., 2020a[10]	Corn-SBM	DDGS	66-134	6.4-15.7	13.2-16.4	15.7	15.7	NDF
Lerner et al., 2020b[11]	Corn-SBM	DDGS	99-127	4.6-15.2	14.3-16.3	15.2	15.2	NDF
Tolosa et al., 2022	Corn-SBM	DDGS	85-137	3.6-13.0	13.6-14.5	3.6	13.0	NE
Lazaga et al., 2024a[12]	Corn-SBM	DDGS	76-105	6.0-14.6	14.2-16.9	14.6	14.6	NDF
Lazaga et al., 2024a[12]	Corn-SBM	DDGS	105-134	3.5-12.1	13.2-15.9	12.1	12.1	NDF

Lazaga et al., 2024b[13]	Corn-SBM	DDGS	60-87	16.9-7.5	15.1-17.5	16.9	16.9	NDF
Lazaga et al., 2024b[13]	Corn-SBM	DDGS	87-139	1.3-10.9	12.7-15.1	10.9	NS	NDF
Increasing SBM with a constant level of DDGS								
Apple et al., 2017	Corn-SBM	20% DDGS	62-84	0.0-10.3	11.9-15.7	5.0	5.0	Lys
Apple et al., 2017	Corn-SBM	20% DDGS	84-100	0.0-6.5	12.0-14.8	NS	NS	N/A
Holen et al., 2022	Corn-SBM	25% DDGS	98-125	0.0-16.0	13.7-19.1	NS	NS	N/A
Faccin et al., 2023	Corn-SBM	20% DDGS	39-67	18.2-34.3	19.9-25.6	NS	NS	N/A
Faccin et al., 2023	Corn-SBM	10% DDGS	102-127	9.5-21.6	14.3-18.6	NS	NS	N/A
Giacomini et al., 2024	Corn-SBM	30% DDGS	32-59	3.9-30.6	16.3-25.6	NS	NS	N/A
Giacomini et al., 2024	Corn-SBM	15% DDGS	80-134	0.0-19.2	11.2-17.9	NS	6.4	N

---

[1] Increasing SBM concentration beyond this level resulted in no further improvement in ADG within each individual trial.

[2] Increasing SBM concentration beyond this level resulted in no further improvement in G:F within each individual trial.

[3] Reducing SBM below the minimum level to support growth performance resulted in this nutrient, or anti-nutritional factor, reducing growth performance.

[4] NS; no statistical difference observed between dietary treatments. N/A; based on the statistical response, no nutrients were present in a deficient quantity.

[5] Net Energy (NE) was considered limiting when reducing SBM concentration below the minimum level for growth performance or carcass characteristics resulted in an increase in ADFI and worsened feed efficiency, with no statistical difference observed in average daily gain.

[6] Neutral Detergent Fiber (NDF) was considered limiting when reducing SBM concentration below the minimum level for growth performance or carcass characteristics resulted in a reduction in ADFI and ADG.

[7] Pigs fed the dietary treatment containing 4.2% SBM attempted to increase intake to compensate for low dietary NE, however GIT capacity appeared to limit intake, thus pigs were not able to attain a similar average daily gain.

[8] The dietary treatments containing 10.7%, or less, SBM had reduced HCW and 10th rib backfat depth.

[9] The dietary treatments containing less than 16.7% SBS had reduced HCW, carcass yield, and loin depth.

[10] The dietary treatment containing 6.4% SBM had reduced HCW and 10th rib backfat depth.

[11] The dietary treatment containing 4.6% SBM had reduced HCW and carcass yield.

[12] The dietary treatments containing less than 14.6 and 12.1% SBM in 76-kg to 105-kg and 105- to 134-kg pigs, respectively, reduced HCW, carcass yield, and loin depth.

[13] The dietary treatments containing less than 10.9% SBM reduced HCW, carcass yield, and backfat depth, but improved carcass lean percentage.

Table 3.3. Summary of the optimal SBM level during periods of heat stress

Item	Major ingredients	BW Range, kg	SBM Range, %	CP Range, %	Minimum SBM level to support: ADG[1]	G:F[2]	Limiting factor[3]
No response							
Lopez et al., 1994	Corn-SBM	70-105	1.5-11.8	8.7-12.7	NS[4]	NS	N/A[4]
Lopex et al., 1994	Corn-SBM	70-105	16.2-26.1	14.5-18.3	NS	NS	N/A
Kerr et al., 2003	Corn-SBM	23-40	11.1-21.1	13.0-16.2	NS	NS	N/A
Wolp et al., 2012	Corn-SBM	37-66	24.4-30.7	15.5-18.0	NS	NS	N/A
de Oliveira et al., 2023	Corn-SBM	68-93	11.7-24.9	13.2-18.4	NS	NS	N/A
de Oliveira et al., 2023	Corn-SBM	93-113	7.8-19.8	12.3-16.9	NS	NS	N/A
Le Bellego et al., 2002	Wheat-Corn-SBM	27-65	13.6-26.6	15.6-20.1	NS	NS	N/A
Le Bellego et al., 2002	Wheat-Corn-SBM	65-101	8.2-20.8	13.3-17.5	NS	NS	N/A
Negative response							
Morales et al., 2018	Wheat-SBM	30-60	4.0-30.3	13.9-21.7	NS	4.0	NE
Morales et al., 2018	Wheat-SBM	30-60	10.0-20.5	16.1-19.0	NS	10.0	NE
Positive response							
Myer et al., 2008	Corn-SBM	52-100	7.8-17.8	11.1-15.1	17.8	NS	Val, Ile, Total N

[1] This SBM concentration resulted in a statistical improvement for ADG within each individual trial.

[2] This SBM concentration resulted in a statistical improvement for G:F within each individual trial.

[3] Primary factor believed to be responsible for reduced growth performance when in each individual trial.

[4] NS; no statistical difference observed between dietary treatments. N/A; based on the statistical response, no nutrients were present in a deficient quantity.

Chapter 4 - Effect of lactation feeder design on sow and litter performance, feeder cleaning criteria, and economic return

Abstract

A total of 557 mixed parity sows (PIC 1050) were used to evaluate the effect of lactation feeder design on sow farrowing performance, litter growth performance, feeder cleaning criteria, and economics. The experiment was conducted during the summer of 2023 at a commercial sow farm located in northwest Texas. The study used two sequential farrowing groups with approximately 279 sows per group. On approximately days 112 to 114 of gestation, sows were moved to the farrowing house and randomly allotted to one of three feeder types based on parity and caliper score. Feeder types consisted of 1) a dry feeder with a nipple drinker located next to the feeder, 2) a wet–dry feeder with a divider to separate feed and water, or 3) a wet–dry feeder without a divider. The three feeder types were used in one of every three stalls with the same sequence from the front to the end of all rooms to balance for environmental effects. Sows were weighed before entering the farrowing house and at weaning. Sows were provided approximately 1.81 kg per day of a common lactation diet prefarrowing, and after farrowing, sows were provided ad libitum access to lactation feed. There was no evidence of a difference in sow weight at entry or weaning, overall BW change, caliper score at entry or weaning, total litter weight or individual pig weight at birth, total pigs born, or percentage of pigs born alive. However, sows fed with the dry lactation feeder had decreased ($P < 0.05$) total daily feed disappearance and average daily feed disappearance compared to either wet–dry feeder design. There was no evidence of difference for litter or pig weaning weight, or litter average daily gain. As a result, litter feed efficiency was improved ($P < 0.05$) for sows fed via the dry feeder compared to either wet–dry feeder. For feeder cleaning criteria, dry feeders had increased (P <

0.05) washing time and washing cost compared to either wet–dry feeder design. In addition, sows fed via the dry feeder had decreased ($P < 0.05$) total lactation feed cost and feed cost per piglet weaned compared to either wet–dry feeder design. In summary, using the wet–dry feeder design in this study with or without a divider separating the feed from the water increased feed disappearance with no effects on sow and litter performance compared to dry feeders, thus worsening litter feed efficiency and increasing feed cost per sow and litter.

Key Words: Feed intake, lactation feeder, litter performance, sow, wet-dry feeder

Introduction

Maximizing feed intake during lactation is crucial to pro mote high levels of milk production for litter growth while simultaneously minimizing body reserve mobilization, thus improving sow longevity and subsequent reproductive performance (Patterson et al., 2011; Tokach et al., 2019). Multiple factors can affect sow feed intake, including genetics, litter size, and environmental conditions (Peng et al., 2007; Tokach et al., 2019; Bjerg et al., 2020). One factor that has received renewed attention in recent years is lactation feeder type and design. While there are numerous types of lactation feeders on the market, a good feeder design can help improve sow feed intake while reducing feed wastage (Rao et al., 2023). In growing-finishing pigs, wet–dry feeders that provide the pig with access to feed and water in the same location have been shown to increase average daily feed intake (ADFI) and average daily gain (ADG) when compared to pigs fed using a conventional dry feeder (Bergstrom et al., 2012a, 2014; Greiner et al., 2022). However, there is limited data on the effects of using a wet–dry feeder during lactation. The existing literature has observed increased lactation feed disappearance for sows fed via a wet–dry feeder compared to a dry feeder, but these trials were not conducted using modern ad libitum feeders (O'Grady et al., 1978; Pettigrew et al., 1985; Peng et al., 2007). Our hypothesis was that because wet–dry feeders increase ADFI of finishing pigs compared to those fed with a dry feeder, the same might be true for lactating sows. Therefore, the objective of this experiment was to compare farrowing performance, litter growth performance, and feeder cleaning criteria of sows fed with a dry feeder vs. two wet–dry feeder designs.

Materials and Methods

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment (IACUC #4535). The experiment was conducted at a commercial sow farm located in northwest Texas. There were 72 stalls per room and a total of four farrowing rooms (288 stalls; 96 stalls per lactation feeder treatment) used for each group. The trial was conducted in two sequential farrowing groups for a total of 576 sows (PIC 1050, Hendersonville, TN) enrolled on the test. Farrowing crates equipped with the dry feeder was also equipped with 1 nipple waterer placed at shoulder height approximately 40 cm from the feeder, while farrowing crates equipped with either wet–dry feeder did not have an additional water source for the sow. All crates were equipped with a nipple waterer at the base of the farrowing crate for piglets. The first group of sows farrowed between June 7 and June 17, 2023, and pigs were weaned between June 29 and July 4, 2023. The second group of sows farrowed between July 4 and July 13, 2023, and pigs were weaned between July 27 and August 1, 2023.

Animals and Treatments

On approximately days 112 to 114 of gestation, sows were moved from the gestation facility into the farrowing house and randomly allotted to one of three lactation feeder types based on parity and caliper score (Knauer and Baitinger 2015), with sow serving as the experimental unit. Each of the three feeder types was equipped with the SowMax ad-lib sow feed hopper (SKU: 7150890500; Hog Slat; Newton Grove, NC). This feed hopper consisted of a rectangular metal box with a rod-like structure at the bottom of the hopper. This was installed on the farrowing stall headgate, with the bottom of the metal box matching approximately the top edge of the feeder bowl. For feed delivery, sows were required to push the rod from side to side, which moved internal parallel plates that allowed feed to drop from the feed hopper to the feeder bowl. When not triggered by the sows, the plates restricted the feed from flowing to the feeder bowls. The adjustment for the feed hopper was controlled by adjusting the distance between the plates. On the side of the metal box, there were six distance settings from 0 to 5, with 0 being fully closed, restricting all feed flow, and 5 allowing greatest feed flow (Rao et al., 2023). Feeder types consisted of 1) a dry lactation feeder with a separate nipple drinker available adjacent to the feeder; 2) a wet–dry lactation feeder with a divider to separate feed and water; or 3) the wet–dry lactation feeder without a divider (Figure 1). The wet–dry feeders had a nipple drinker located near the bottom of the feeder to allow sows free access to water. The three feeder types were placed in the farrowing stalls in the same sequence (Dry, wet–dry with divider, wet–dry without divider) from the front to the end of all farrowing rooms to balance and minimize any environmental effects in each room. The same sorghum-soybean meal-based commercial lactation feed was fed to all sows (Table 4.1). Prefarrowing, sows were provided approximately 0.905 kg in the morning and afternoon, for a total of 1.81 kg per day, of the lactation diet. After farrowing, sows were provided ad libitum access to the lactation diet. The hopper of each feeder was filled twice a day, and each feed addition was weighed and electronically recorded. Feed addition to each feeder was registered to the stall with the date and weight recorded for calculating feed disappearance. Feeder adjustments were made daily to achieve approximately 50% feed coverage on the base of the feeder bowl. Feeder bowls were checked twice daily for wet or moldy feed, and this was removed when necessary. The spoiled feed was not weighed and, therefore, was counted as a portion of the total feed disappearance. Viable pigs were individually tagged with an RFID tag within 24 h of birth. The average weaning age was 20.9 d

Data and sample collection

All animal and feed scales used in this trial were calibrated daily and verified with test weights to assure accuracy. All feed, sow, and litter data were recorded and stored using the LeeO system (Prairie Systems, Spencer, IA). An RFID tag was attached to each sow stall and identified as a location pen in the LeeO system. Individual information (sow ID, parity, and breeding date) for each sow was exported from the CloudFarms (Bratislava, Slovakia) system and then imported into the LeeO system. A walk-on platform scale was used to weigh sows before entering the farrowing house and at weaning. Sow caliper score was taken between days 109 and 111 of gestation (Knauer and Baitinger 2015). Caliper scores 6 to 12, 12 to 17, and 17 to 22 correspond to body condition scores of 1, 2, and 3, respectively. When sows were moved to the farrowing stall, they were also registered in the location pens in the LeeO system. Feed carts equipped with scales were used to obtain the weight of each feed addition. Feed additions were registered to the stall (location pen) with date and weight recorded for calculating total feed disappearance. Total feed disappearance was calculated by subtracting left over feed in the feed hoppers at weaning from the cumulative feed additions during the lactation period. Total feed disappearance represents the combination of feed intake and feed wastage. The number of sows bred back by days 7, 14, and 30 were obtained from the CloudFarms system. Sows that were culled at weaning for any reason were not included in the subsequent farrowing data analysis.

For litter performance, piglets were registered under the sow and location pen and were weighed individually at birth and at weaning. Nonviable piglets (under 0.68 kg body weight (BW) or dead before tagging), stillborn, and mummies were recorded but not included in the total litter weight. Any cross-fostering and mortalities throughout the lactation period were recorded. After weaning, 3 farm employees were designated to wash feeders, and cleaning times were recorded. The number of feeders evaluated was 59, 57, and 57 for the dry feeder, wet dry feeder with a divider, and wet–dry feeder without a divider, respectively. For economic data, the lactation diet cost was $363/tonne, the litter value was $1.54/kg of litter weight, and the labor cost for washing was $23/h

Statistical Analysis

For sow BW data, approximately 147 sows were used per treatment with an average parity of 1.9. Sows not included in the analysis of BW data were because of missing data points for their weaning weight. This was due to either culling or mortality prior to weaning. For feed disappearance, approximately 170 sows were used per treatment. Sows not included in the analysis of feed disappearance were a result of culling, mortality, or movement to another stall prior to weaning. For litter performance data, approximately 159 sows were used per treatment. Sows not included in the analysis of litter data were a result of missing data points for litter birth weight, weaning weight, culling, or mortality prior to weaning. Data were analyzed using a generalized randomized block design for one-way ANOVA in the R Studio program. The lmer function from the lme4 package was used for lactating sow BW, sow caliper, feed disappearance, and litter growth performance. The glmer function (Poisson distribution) from the lme4 package was used for total born and litter size. The glmmTMB function (beta-binomial distribution) from the glmmTMB package was used for the percentage of mortality and pigs weaned. Sow (litter) was considered as the experimental unit. Farrowing room and group were the blocking factors for sow and litter data. The lactation feeder design was used as the fixed effect. Sow entry weight was used as a covariate for sow day 1 weights, weaning weight, and weight change data. The parity category (P1, P2, or P3+) was tested as a covariate for sow BW, feed intake, litter weights and growth performance, and economic variables and was included in the model when the Bayesian Information Criterion was decreased by at least 2.0. A Tukey's/Sidak multiple comparison adjustment was used to control type I error rate. All results were considered significant at $P \leq 0.05$ and marginally significant at $0.05 < P \leq 0.10$.

Results

There was no evidence of a difference in sow weight or caliper score on day 112 of gestation, at farrowing, or weaning, or their changes during lactation (Table 4.2). Total litter or pig birth weight, total pigs born, or pigs born alive as a percentage of total born, viable born, nonviable born, stillborn, or mummified pigs were not different amongst sows fed via the three lactation feeder designs. Litter or pig weaning weight or litter average daily gain were also not affected by lactation feeder design. However, sows fed via the dry lactation feeder had decreased ($P < 0.05$) total feed disappearance and average daily feed disappearance compared to those fed with either wet–dry feeder. As a result, litter feed efficiency was improved ($P < 0.05$) in sows fed with the dry feeder compared to those fed with the wet–dry feeders. In addition, sows fed with the dry feeder had decreased ($P < 0.05$) total lactation feed cost and feed cost per pig weaned compared to sows fed with either wet–dry feeder.

There was no evidence for difference ($P > 0.10$) in subsequent reproductive performance (percentage bred by days 7, 14, and 30) between sows fed via the different feeder designs.

Washing time and cost were greater ($P < 0.05$) for the dry feeders compared to both wet–dry feeder designs.

Discussion

Our hypothesis for initiating this study was based on the observations that growing-finishing pigs fed with a wet–dry feeder have greater growth rate and feed intake compared to those fed via a dry feeder (Nitikanchana et al., 2012; Myers et al., 2013; Bergstrom et al., 2014). The increased ADFI observed when using a wet–dry feeder is suggested to be a result of changes in feeding behavior, namely increased eating speed/reduced feeding duration resulting in the consumption of larger meals (Gonyou and Lou 2000; Hurst et al., 2008; Bergstrom et al., 2012b). We speculated that the same might be true during lactation. Rao et al. (2023) compared three ad libitum dry feeder designs on sow and litter performance. They observed that sows fed via the SowMax hopper with a curved feeder bowl had decreased feed disappearance and improved litter feed efficiency compared with those fed via an ad libitum PVC tube feeder also equipped with a curved feeder bowl. Therefore, we selected the SowMax hopper with a curved bowl and an adjacent waterer (as used by Rao et al. 2023) as our control feeder to compare wet–dry bowls that either divided water from feed or mixed feed and water.

The limited data on the effect of wet–dry feeders on lactation performance has shown positive results. However, many of these studies compared ad libitum-fed wet–dry feeders to hand- or limit-fed dry feeders and thus may not be applicable to modern sow farms that utilize ad libitum self-feeders in the farrowing house. Peng et al. (2007) observed that sows using a wet–dry feeder had increased feed disappearance and litter ADG. These improvements were suggested to be a result of sows having the ability to choose when and how much to eat and the ability to adjust the moisture level of each meal. However, as feed was only provided twice per day to sows using the conventional dry feeder, these sows may have had unintentionally limited feed availability. Thus, it is difficult to determine if feeder type, or feed accessibility, was the primary factor behind the improved performance. Pettigrew et al. (1985) also observed that sows fed using an ab libitum self-fed wet–dry feeder had increased feed disappearance and litter weight gain compared to sows fed by hand in conventional dry feeders. The hopper above feeders in our study allowed sows to have continual access to feed throughout the entire lactation period.

Due to labor limitations in this study, we were not able to separate actual feed intake from feed wastage, thus, data are presented as feed disappearance. In our study, the increased feed disappearance for sows using wet–dry feeders was not used by the sow because we observed no differences in litter growth rate or change in sow weight or caliper score. We believe that actual feed intake was similar between sows using all lactation feeder designs, but the greater disappearance was due to feed wastage for sows fed with wet–dry feeders. The proposed increase in feed waste when sows were fed using the wet–dry feeders led to a significant worsening of litter feed efficiency. The differences in feed wastage may have been due to excess water in the feeder bowl resulting in spilled feed, or due to greater quantities of spoiled feed removed from the wet–dry feeders by employees on a day to-day basis. Spoiled feed was removed from feeders as it has been noted to increase feed refusal, thus reducing sow performance (Kanora and Maes, 2009). We believe this was largely due to the location of the nipple waterer within the wet–dry feeder, as feed particles may have gotten stuck in the nipple, causing excess water to collect in the bowl. From an economic perspective, the increased feed disappearance resulted in a 9% increase in total lactation feed cost for the wet–dry feeders compared to the dry feeder. As there were no improvements in litter growth or preweaning mortality, feed cost per pig weaned was increased (P = 0.006) for sows using the wet–dry feeders.

Another factor that must be considered when implementing a new feeder type into a commercial sow farm is the potential change in cleaning difficulty as this can affect the time required to clean feeders (Rao et al., 2023). Rao et al. (2023) observed a high amount of variability in cleaning times, largely due to variation from person to person, which reduced their ability to find differences in mean cleaning time between the different lactation feeders. We had a much lower degree of variability in our study and thus observed that the wet–dry feeders used in this experiment required significantly less time to clean compared to the dry feeder. This difference may be due to the differences in the shape of the feed pan between feeder types. As the dry feeder had a curved design to the bottom of the feed pan, a greater amount of time was required to successfully remove residual feed material as op posed to the flat design of the wet–dry feed pans.

In conclusion, the lack of differences in litter growth performance and sow weight change suggests that sows had similar true feed intake, regardless of feeder design. Therefore, the increased feed disappearance observed when sows were fed with either wet–dry feeder design used in this study appears to be due to increased feed wastage. As a result, sows using the dry feeder had improved litter feed efficiency and economic savings. Thus, transitioning existing sow farms to wet–dry feeders used in this study may not be economically justified.

References

Bergstrom, J. R., J. L. Nelssen, M. D. Tokach, S. S. Dritz, R. D. Goodband, and J. M. DeRouchey. 2012a. Effects of two feeder designs and adjustment strategies on the growth performance and carcass characteristics of growing-finishing pigs. J. Anim. Sci. 90:4555-4566. doi:10.2527/jas2011-4485.

Bergstrom, J. R., J. L. Nelssen, L. N. Edwards, M. D. Tokach, S. S. Dritz, R. D. Goodband, and J. M. DeRouchey. 2012b. Effects of feeder design and changing source of water to a location separate from the wet-dry feeder at 4 or 8 weeks before harvest on growth, feeding behavior, and carcass characteristics of finishing pigs. J. Anim. Sci. 90:4567-4575. doi:10.2527/jas2011-4486.

Bergstrom, J. R., J. L. Nelssen, M. D. Tokach, S. S. Dritz, R. D. Goodband, and J. M. DeRouchey. 2014. The effects of feeder design and dietary dried distillers' grains with solubles on the performance and carcass characteristics of finishing pigs. J. Anim. Sci. 92:3591-3597. doi:10.2527/jas2014-7686.

Bjerg, B., P. Brandt, P. Pendersen, and G. Zhang. 2020. Sows' responses to increased heat load - A review. J. Therm. Biol. 94:102758. doi:10.1016/j.therbio.2020.102758.

Gonyou, H. W., and Z. Lou. 2000. Effects of eating space and availability of water in feeders on productivity and eating behavior of grower/finisher pigs. J. Anim. Sci. 78:865-870. doi:10.2527/2000.784865x.

Greiner, L. L., D. C. Humprey, S. Becker, C. S. Hagen, and K. Holtz. 2022. Evaluation of novel wet/dry feeder in finishing pigs. J. Anim. Sci. 100(Suppl. 2):45-46. doi:10.1093/jas/skac064.071.

Hurst, D., L. Clarke, and I. J. Lean. 2008. Effect of liquid feeding at different water-to-feed ratios on the growth performance of growing-finishing pigs. Animal. 2:1297-1302. doi:10.1017/S175173110800253X.

Kanora, A., and D. Maes. 2009. The role of mycotoxins in pig reproduction: a review. Vet. Med. 54:565-576. doi:10.17221/156/2009-VETMED.

Knauer, M. T., and D. J. Baitinger. 2015. The sow body condition caliper. Appl. Eng. Agric. 31:175-178. doi:10.13031/aea.31.10632.

Myers, A. J., R. D. Goodband, M. D. Tokach, S. S. Dritz, J. M. DeRouchey, and J. L. Nelssen. 2013. The effects of diet form and feeder design on the growth performance of finishing pigs1,2. J. Anim. Sci. 91:3420-3428. doi:10.2527/jas.2012-5612.

Nitikanchana, S., S. S. Dritz, M. D. Tokach, J. M. DeRouchey, R. D. Goodband, and J. L. Nelssen. 2012. Meta-analysis comparing growth performance, carcass characteristics, and water usage of growing-finishing pigs fed using conventional dry and wet-dry feeders. In: Proc. 22nd International Pig Veterinary Society, Jeju, South Korea.

O’Grady, J. F., P. B. Lynch, and P. A. Kearney. 1978. Voluntary feed intake by lactating sows: influence of system of feeding and nutrient density of the diet. Irish J. Agric. Res. 12:355-365. doi:10.1016/0301-6226(85)90134-4.

Patterson, J. L., M. N. Smit, S. Novak, A. P. Wellen, and G. R. Foxcroft. 2011. Restricted feed intake in lactating primiparous sows. I. Effects on sow metabolic state and subsequent reproductive performance. Reprod. Fertil. Dev. 23:899-898. doi:10.1071/RD11015.

Peng, J. J., S. A. Somes, and D. W. Rozeboom. 2007. Effect of feeding and watering on performance of lactating sows. J. Anim. Sci. 85:853-860. doi:10.2527/jas2006-474.

Pettigrew, J. E., R. L. Moser, S. G. Cornelius, and A. F. Sower. 1985. Feed intake of lactating sows as affected by feeder design. Minnesota Swine Research Reports AG-BU-2300. St. Paul.

Rao, Z. X., K. F. Coble, M. D. Tokach, J. C. Woodworth, J. M. DeRouchey, R. D. Goodband, and J. T. Gebhardt. 2023. Effect of different sow lactation feeder types and drip cooling on sow body weight, litter performance, and feeder cleaning criteria. Transl. Anim. Sci. 7:1-9. doi:10.1093/tas/txad040.

Tokach M. D., M. B. Menegat, K. M. Gourley, and R. D. Goodband. 2019. Review: Nutrient requirements of the modern high-producing lactating sow, with an emphasis on amino acid requirements. Animal. 13:2967-2977. doi:10.1017/S1751731119001253.

Table 4.1. Diet composition (as-fed basis)[1]

Item	Lactation diet
Ingredients, %	
Sorghum	64.21
Soybean meal, 46.5% CP	25.50
Corn distillers dried grains with solubles	5.00
Corn oil	1.50
Limestone	1.55
Monocalcium P (21% P)	0.70
Sodium chloride	0.55
Lysine, 60%[2]	0.44
Methionine hydroxy analogue[3]	0.08
L-Thr	0.08
Vitamin and trace mineral premix	0.25
Choline chloride	0.11
Phytase[4]	0.04
Total	100.00
Calculated analysis	
Standardized ileal digestibility AA, %	
Lys	1.05
Ile:Lys	68
Leu:Lys	148
Met:Lys	30
Met and Cys:Lys	53
Thr:Lys	64
Trp:Lys	20.0
Val:Lys	75
His:Lys	39
Total Lys, %	1.18
NE, kcal/kg	2,562
SID Lys:NE, g/Mcal	4.10
CP, %	19.4
Ca, %	0.80
P, %	0.54
STTD P, %	0.43

[1] Feed was manufactured by a commercial feed mill (JBS, Dalhart, TX).

[2] BioLys (Evonik Industries AG, Essen Germany).

[3] MHA (Novus International, Inc. Chesterfield, MO).

[4] OptiPhos Plus 2500 G (Huvepharma, Peachtree City, GA), provided 902 FTU/kg of diet, for an estimated release of 0.11% STTD P.

Table 4.2. The effect of lactation feeder design on sow and litter performance

	Feeder Design				
	Dry	Wet-dry			
Divider:		Yes	No	SEM	*P* =
Sow body weight, kg					
Sows, n	154	143	143		
Entry[2]	233.9	234.5	233.7	1.87	0.950
d 1[2,3,4]	196.6	197.0	196.0	0.91	0.739
Weaning[2,4]	195.2	197.7	196.6	1.35	0.310
Weight change					
Entry-weaning[2,4]	-38.8	-36.3	-37.4	1.35	0.310
Weight change, %[2,4]	-16.6	-15.2	-15.8	0.60	0.172
d 1 - weaning[2,3,4]	-1.2	0.7	0.7	1.63	0.550
Weight change, %[2,3,4]	-0.4	1.1	1.0	0.90	0.344
Sow caliper score					
Entry	14.6	14.7	14.7	0.18	0.889
Weaning	12.5	12.8	12.7	0.19	0.526
Change (entry to wean)	-2.0	-1.8	-2.1	0.21	0.500
Feed disappearance					
Sows, n	170	169	170		
Total feed disappearance, kg[2]	118.9^{b}	128.4^{a}	130.6^{a}	3.41	< 0.001
Average daily feed disappearance, kg[2]	5.6^{b}	6.1^{a}	6.2^{a}	0.10	< 0.001
Litter performance					
Sows, n	161	158	157		
Total born, n	16.6	16.6	16.8	0.34	0.852
Live born, %	91.3	91.0	90.8	0.66	0.827
Viable born, %	88.8	88.3	88.7	0.65	0.820
Nonviable born, %[5]	2.4	2.7	2.1	0.31	0.380
Stillborn, %	5.7	6.1	6.4	0.51	0.580
Mummified, %	3.0	2.9	2.8	0.34	0.914
Litter size after cross-fostering, n	14.8	14.8	14.8	0.31	0.979
Litter birth weight, kg[2]	21.11	20.81	20.98	0.435	0.754
Pig birth weight, kg[2]	1.42	1.42	1.42	0.037	0.937
Lactation length, d	21.0	20.8	20.8	0.57	0.894
Litter weaning weight, kg[2]	76.00	76.88	77.57	1.398	0.506
Pig weaning weight, kg[2]	5.90	5.90	5.90	0.096	0.995
Litter weight gain, kg[2]	54.88	56.07	56.59	1.341	0.369
Litter average daily gain, kg[2]	2.62	2.69	2.73	0.067	0.182
Litter feed efficiency[2,6]	0.474^{a}	0.448^{b}	0.445^{b}	0.011	0.015
No. weaned	12.9	13.0	13.2	0.29	0.799
Weaned, %	86.8	88.5	88.9	0.81	0.135
Pre-weaned mortality, %[7]	13.2	11.5	11.1	0.81	0.135
Economics, $[8]					
Litter value[2]	117.3	118.6	119.7	2.16	0.506
Total lactation feed cost[2]	46.08^{b}	49.92^{a}	50.46^{a}	1.25	< 0.001

Litter value over lactation feed cost[2]	71.82	70.30	69.59	2.06	0.561
Feed cost per pig weaned[2]	3.63^{b}	3.85^{a}	3.89^{a}	0.095	0.006
Feed cost per lb of litter weight gain[2]	0.39	0.41	0.41	0.010	0.112
Washing time per feeder, s	45.9^{a}	40.0^{b}	40.3^{b}	4.67	0.001
Washing cost per feeder	0.28^{a}	0.25^{b}	0.25^{b}	0.029	0.001
Sow subsequent performance					
Sows, n	157	151	139		
Bred by 7 d, %	73.2	74.3	78.7	6.99	0.524
Bred by 14 d, %	76.1	76.6	81.7	6.76	0.446
Bred by 30 d, %	85.1	85.4	89.0	4.09	0.534

[a,b] Means within a row with different superscripts differ ($P \le 0.05$).

[1] A total of 557 mixed parity sows (PIC 1050; average parity 1.9) that were bred to PIC 337 boars were used. Sow caliper score was taken between d 109 and 111 of gestation and sows were allotted to treatment based on parity and caliper score.

[2] Parity category (P1, P2, or P3+) was used as a covariate.

[3] Day 1 weight estimated as: entry weight – (litter birth weight + estimated weight of conceptus). Conceptus weight estimated using the equation proposed in NRC 2012. Weigh of conceptus (g) = exp (8.621 – 21.02 × exp (-0.053 × days of gestation) + 0.114 × total born) × Ratio.

Ratio = (total born × average piglet birth weight, g) / 1.12 × exp {[9.095 – 17.69 exp (-0.0305 × 114) + 0.0878 × total born]}

[4] Entry BW was used as a covariate.

[5] Nonviable pigs consisted of those born with an injury, a deformity, or under 0.68 kg BW.

[6] Litter feed efficiency = Lactation feed disappearance ÷ total litter weight gain.

[7] Pre-weaned mortality, % of litter size = [(dead after cross-fostering) ÷ (litter size at 24 h)] × 100%

[8] Lactation feed cost was $330/ton, and the labor cost for washing was $23/h. Litter value = litter weaning weight × $1.54/kg.

Figure 4.1. Sow lactation feeders. Dry feeder, wet-dry feeder with divider, and wet-dry feeder without divider (from left to right). All feeders were equipped with the SowMax ad-lib sow feed hopper which has a rod that can be pushed sideways, opening a gap on the sides of the hopper to allow feed to drop.

Chapter 5 - Effects of replacing lactose with novel carbohydrate sources on nursery pig growth performance and feed intake preference

Abstract

Two experiments were conducted to determine the effect of replacing lactose in nursery pig diets with novel carbohydrate products (CHO-D and CHO-L; Cargill Starches, Sweeteners, & Texturizers, Blair, NE) on growth performance and feed intake preference. In Exp. 1, 360 barrows (initially 6.0 ± 0.04 kg) were allotted to pens in 2 weight blocks, and pens were allotted to 1 of 6 dietary treatments. Dietary treatments were corn-soybean meal-based with 5 to 7.5% DDGS and included: 1) negative control (NC; containing approximately 0% sugar); 2) positive control (PC; containing 10 and 5% lactose, phase 1 and 2, respectively); 3 and 4) 50 or 100% replacement of lactose with the dry CHO (50% CHO-D; 100% CHO-D); and 5 and 6) 50 or 100% replacement of lactose with the liquid CHO (50% CHO-L; 100% CHO-L). Lactose was provided via whey powder and whey protein concentrate. There was no effect of diet on ADG, ADFI, or G:F. In Exp. 2, 300 pigs (initially 5.6 ± 0.59 kg) were used in three, 3-d periods to determine the effect of CHO sources on feed intake preference. Pigs were allotted to 2 weight blocks, and on d 3, 9, and 17 post-weaning, pens were allotted to 1 of 3 dietary comparisons in a completely randomized design, with 20 replications per comparison per period. The same PC, 100% CHO-D, and 100% CHO-L phase 1 and 2 diets from Exp. 1 were used in Exp. 2, with phase 1 diets fed from d 3 to 6 and 9 to 12, and phase 2 diets being fed from d 17 to 20. During each period, dietary comparisons included: 1) PC vs. CHO-D; 2) PC vs. CHO-L; and 3) PC vs. PC to test the effect of feeder location within pen. For comparison 1, pigs tended (P = 0.060) to prefer the diet with CHO-D compared to the PC, on a percentage intake basis during phase 1. However, in phase 2 ($P = 0.001$) pigs preferred the PC diet compared to the CHO-D diet. For comparison 2, in all phases pigs preferred ($P < 0.001$) the PC diet compared to the CHO-L diet. In summary, pigs preferred CHO-D over the PC in phase 1, while the inverse was true in phase 2, but pigs preferred the PC diet over the CHO-L diet in all phases. Nevertheless, when pigs were not given the choice of diets (Exp. 1), pigs fed diets containing the novel CHO products had similar performance to those on the PC treatment, but we were also unable to detect benefits of lactose as the PC treatment did not differ from the NC treatment. Thus, we could not conclude whether the novel CHO products are suitable replacements for traditional lactose sources.

Key Words: Carbohydrate, growth, lactose, nursery pig, preference, sugar

Introduction

Weaning is largely considered the most stressful time in a pig's life as the piglet is subjected to a variety of stressors. Key among these is the dramatic change in diet composition as the pig is transitioned from a liquid, milk-based diet to a dry, cereal-based diet. This often leads to reduced feed intake and a lag in growth performance. Therefore, highly palatable and digestible ingredients, such as milk-based products, are often included in the diets of early nursery pigs. Numerous researchers have observed that inclusion of milk-based products, such as dried whey powder (73% lactose) improves growth performance and health of nursery pigs (Mahan et al., 2004; Cromwell et al., 2008; Naranjo et al., 2010). Additionally, it has been determined that the carbohydrate (CHO) portion of milk-products (lactose) is the primary factor behind these improvements in growth performance (Mahan et al., 1992). This response is primarily due to the high lactase activity in the small intestine of the newly weaned pig which makes lactose more easily digested than more complex CHOs like starch (Tokach et al., 1995). However, traditional lactose sources are historically relatively expensive to include in the diet, leading producers and researchers to seek alternative ingredients to lower feed cost while easing the dietary transition post-weaning.

Alternative simple CHO sources have garnered attention as potential replacements to lactose, as it has been demonstrated that at least a portion of lactose can be replaced with other sugar sources without negative effects on growth performance (Dunmire et al., 2020). Including simple sugar sources such as dextrose, sucrose, fructose, and products that are combinations of multiple CHO's into nursery diets has resulted in similar levels of growth performance as diets that contained lactose (Mavromichalis et al., 2001; Naranjo et al., 2010; Guo et al., 2015). Moreover, it has been shown that both sucrose and lactose can stimulate the appetite of weanling pigs (Cromwell et al., 2008). However, multi-choice preference trials have observed that nursery pigs may prefer diets containing sucrose over those containing a traditional lactose source (Diaz et al., 1956; Glaser et al., 2000). The Starches, Sweeteners, and Texturizers division of Cargill produces many CHO products through their corn wet-milling activities, two of which being the CHO-D and CHO-L products tested herein, but it is unknown whether either of the products can elicit beneficial growth performance in weaned pigs. Both products are combinations of mono- and di-saccharides, with CHO-D being 97% DM made up of primarily non-reducing sugars, and CHO-L being 77% DM containing primarily reducing sugars. Therefore, the objective of these studies was to determine the effects of replacing lactose in phase 1 and 2 nursery diets with 1 of 2 novel CHO products on growth performance and feed intake preference. Our hypothesis is that replacing a traditional lactose source with either novel CHO source will elicit similar growth performance and feed intake preference.

Materials and Methods

General

The Kansas State University Animal Care and Use Committee approved the protocol used in these experiments. Experiments were conducted at the Kansas State University Segregated Early Weaning Research Facility and the Kansas State University Swine Teaching and Research Center in Manhattan, KS. The facilities were totally enclosed and environmentally regulated. In Exp. 1, each pen (1.21 × 1.21-m) was equipped with a 4-hole, dry self-feeder, and cup waterer for *ad libitum* access to feed and water. Pens were located over a metal tri-bar floor with a 1.21-m pit underneath for manure storage. In Exp. 2, to determine feed intake preference, each pen (1.21 × 1.21-m) was equipped with either two 4-hole, dry self-feeders, or two 2-hole, dry self-feeders, and nipple waterer for *ad libitum* access to feed and water. Both feeders within each pen were of the same design. Feeder location was not rotated daily, as is sometimes practiced, to avoid disruption of preference patterns of pigs. Instead, feeder location remained constant during each experimental period as suggested by Solà-Oriol et al. (2009, 2011). This was to eliminate the need for an adaptation period needed to respond to changes in feeder position and shorten the duration of experiment period. Pens were located over a metal tri-bar floor with a 1.21-m pit underneath for manure storage. All experimental diets were manufactured at Provimi North America in Lewisburg, OH and fed in pellet form. The common Phase 3 diet fed in Exp. 1 was manufactured at Hubbard Feeds in Beloit, KS and fed in meal form.

Experiment 1

A total of 360 barrows (DNA 200 × 400; initially 6.0 ± 0.04 kg BW) were used in a 42-d growth trial. Pigs were weaned at approximately 21 d of age, randomly allotted to pens in 1 of 2 weight blocks based on initial BW (initially 5.4 and 6.6 kg BW), and then allotted to 1 of 6 dietary treatments in a completely randomized design. There were 5 pigs per pen and 12 pens per treatment across 2 barns.

Dietary treatments were corn-soybean meal-based with 5 to 7.5% DDGS and included: 1) negative control (NC; containing < 0.1% lactose in all phases); 2) positive control (PC; containing 10 and 5% lactose, phase 1 and 2, respectively); 3) 50% of lactose replaced with the dry novel CHO (50% CHO-D); 4) 100% of lactose replaced with CHO-D (100% CHO-D); 5) 50% of lactose replaced with the liquid novel CHO (50% CHO-L); or 6) 100% of lactose replaced with CHO-L (100% CHO-L). Novel CHO sources (CHO-D or CHO-L; Cargill Starches, Sweeteners, & Texturizers, Blair, NE) replaced whey powder on a carbohydrate basis in phase 1 and 2 diets (Tables 1 and 2). Both CHO products are combinations of mono- and di-saccharides, with CHO-D being a 97% DM product made up of primarily non-reducing sugars, and CHO-L being a 77% DM product containing primarily reducing sugars. The NC diet, as well as the 100% CHO-D and 100% CHO-L diets, contained trace amounts of lactose due to the inclusion of whey protein concentrate which was included in the diet to balance CP percentage, and milk proteins, across diets. Additionally, to maintain a consistent level of total CHOs across dietary treatments, greater concentrations of CHO-L were added to account for differences in dry matter. Individual pigs were weighed, and feed disappearance was recorded on d 0, 7, 10, 17, 24, 31, and 42 to determine ADG, ADFI, and G:F.

Fecal samples were collected on d 10 and 24 to determine fecal dry matter percentage from the same three randomly selected pigs from each pen. After collection, fecal samples were dried at 55°C in a forced air oven for 48 h, and the ratio of dried to wet fecal weight was used to determine the fecal dry matter. Fecal samples were maintained separately for each pig for analysis and the average of the three samples from each pen was then used for statistical analysis.

Experiment 2

A total of 300 pigs (600 × 241, DNA; initially 5.6 ± 0.59 kg BW) were used in three 3-d periods to determine feed intake preference based on diets formulated with various CHO sources. Pigs were weaned at approximately 21 d of age, allotted to pens in one of two weight blocks based on initial BW (initially 5.0 and 6.2 kg BW), with 5 mixed gender pigs per pen. The same PC with lactose, 100% CHO-D, and 100% CHO-L phase 1 and 2 diets from Exp. 1 were used in Exp. 2 (Table 1 and 2). Novel CHO sources (CHO-D or CHO-L) replaced the lactose source (whey powder) on a total CHO basis in phase 1 and 2 diets. Phase 1 diets were fed in periods 1 and 2 (d 3 to 6 and 9 to 12, respectively), and phase 2 diets were fed during period 3 (d 17 to 20).

Three 3-d preference periods were conducted with the same 60 pens. Each period used the same set of 300 pigs, which were fed the same NC diet from Exp 1. (containing < 0.1% lactose) for the 3 or 5-d period between experimental periods (Tables 1 and 2). This was done to reduce the carryover effect from one period vs another. On d 3, 9, and 17 after weaning, pigs were individually weighed, and pens were allotted to 1 of 3 dietary comparisons in a completely randomized design. During each period, the dietary comparisons included: 1) PC vs. CHO-D; 2) PC vs. CHO-L; 3) PC vs. PC. During each period, feeder type was balanced across comparisons, such that each comparison had 14 replicate pens containing two 4-hole feeders, and 6 replicate pens containing two 2-hole feeders. Feeder size did not significantly impact feed intake, and as such was not included in the model. Moreover, feeder location within pen was balanced within a dietary comparison to minimize potential for feeder location bias. Feed disappearance was measured daily during each 3-d period to determine average daily feed disappearance per pen of each diet.

Statistical analysis

In Exp. 1, experimental data were analyzed using R Studio (Version 1.3.1093, Rstudio, Inc., Boston, MA) using R programming language [Version 4.0.2 (2020-06-22), R Core Team, R Foundation for Statistical Computing, Vienna, Austria] with pen serving as the experimental unit in a completely randomized design. Treatment, body weight block, and the associated interaction served as fixed effects within the statistical model, with barn serving as a random effect. When treatment was a significant source of variation, differences were determined using pairwise comparisons using the Tukey-Kramer multiplicity adjustment to control for type I error. Fecal DM were analyzed using the fixed effects of day, treatment, and body weight block, and the associated interactions accounting for repeated over time.

In Exp. 2, data were analyzed as a completely randomized design using the R Studio environment (Version 1.3.1093, Rstudio, Inc., Boston, MA) using R programming language [Version 4.0.2 (2020-06-22), R Core Team, R Foundation for Statistical Computing, Vienna, Austria] with feeder within pen as the experimental unit. In comparisons 1 and 2 diet, body weight block, and the associated interaction served as fixed effects within the statistical model with pen serving as a random effect. For comparison 3, which was designed to test the potential effect of feeder location within pen, feeder location, body weight block, and the associated interaction served as fixed effects within the statistical model and pen served as a random effect.

The lmer function of R Studio was used to evaluate within pen mean difference in average daily feed disappearance between the two feeders and was expressed as percentage of the total feed consumed for each diet, or the absolute amount of feed consumed of each diet per feeder. Data were analyzed in two phases; Phase 1 included the first two periods (d 3 to 6 and 9 to 12) and Phase 2 included the third period (d 17 to 20). For both experiments, results were considered significant at $P \leq 0.05$ and marginally significant at $P \leq 0.10$.

Results

Experiment 1

There were no observed weight block × CHO source interactions or main effect of CHO source on BW (d 0, 10, 24, or 42; Table 3). However, pigs in the heavyweight block had greater ($P \leq 0.001$) BW than pigs in the lightweight block at each weighing event. There were no observed weight block × CHO source interactions or main effects of CHO source on the percentage of pigs that lost weight from d 0 to 7. However, there was a tendency ($P = 0.063$) for a greater percentage of pigs in the lightweight block to lose weight compared to those in the heavyweight block.

Throughout the treatment period (d 0 to 24) there was a weight block × CHO source interaction ($P = 0.045$) for ADFI, in which heavyweight pigs fed the PC diet containing lactose had greater ADFI than lightweight pigs fed the same diet, while there was no significant difference due to weight block among the other treatments. There were no observed weight block × CHO source interaction or main effects of CHO source on ADG. There was an observed tendency for a main effect of CHO source ($P = 0.058$) on G:F, but the means did not significantly separate. Moreover, pigs in the heavyweight block had greater ($P < 0.001$) ADG than those in the lightweight block.

During the common period (d 24 to 42), there was no weight block × CHO source interaction or main effect of previously fed CHO source on ADG, ADFI, or G:F. Pigs in the heavyweight block had greater (*P* < 0.001) ADG and ADFI than those in the lightweight block, leading to poorer (*P* = 0.020) G:F.

Overall (d 0 to 42), there was a tendency for a weight block × CHO source interaction (*P* = 0.067) for ADFI, in which heavyweight pigs fed the PC, 100% CHO-D, and 100% CHO-L diets tended to have greater ADFI than lightweight pigs fed the same diet, while there was no difference due to weight block among the other treatments. There was no observed main effect of CHO source on any observed growth performance characteristic. Pigs in the heavyweight block had greater (*P* < 0.001) ADG and ADFI than those in the lightweight block, leading to poorer (*P* = 0.033) G:F. There were no observed 2- or 3-way interactions or any observed main effects of weight block or CHO source on percent fecal dry matter.

Experiment 2

When comparing the PC and CHO-D containing diets, during phase 1 there was no observed interaction nor main effect of weight block or diet on daily feed disappearance (Table 4). However, there was a tendency (*P* = 0.060) for a diet effect on proportion of daily feed intake, in which pigs tended to prefer diets containing CHO-D compared to the diet containing lactose. During phase 2 there was no observed interaction nor main effect of weight block on daily feed disappearance. However, different than observed in phase 1, there was an observed main effect of diet (*P* ≤ 0.001) on feed preference during phase 2, as pigs preferred the diet containing lactose compared to the diet containing CHO-D.

When comparing the PC and CHO-L containing diets, during phase 1 there was no observed interaction nor main effect of weight block on daily feed disappearance. There was a tendency (*P* = 0.073) for a weight block × diet interaction on proportion of feed intake in which lightweight pigs tended to have a greater preference for the lactose-containing diet compared to heavyweight pigs. Additionally, there was a main effect of diet (*P* < 0.001) as pigs preferred the lactose-containing diet over the diet containing CHO-L when measured both as daily feed disappearance and as a proportion of total feed disappearance. During phase 2, there was a weight block × diet interaction on daily feed disappearance (*P* = 0.004) and for proportion of feed disappearance (*P* = 0.064), in which heavyweight pigs had a greater preference for the lactose-containing diet compared to the diet with CHO-L than lightweight pigs. There was also a main effect of diet observed (*P* < 0.001) when reported on both a feed disappearance and proportional basis where pigs preferred the lactose-containing over the diet containing CHO-L. When studying the effect of feeder location on feed intake preference (PC vs. PC), there was no observed effect of feeder location on daily feed disappearance indicating feeder location within pen did not influence feed intake preference.

Discussion

Weaning is a stressful event, often leading to a disruption in nutrient intake during the first 3 to 5 d post-weaning, commonly referred to as the post-weaning growth check (Wensley et al., 2021). One of the leading causes for this disruption in feed intake is the rapid transition from a liquid, milk-based diet to a dry, cereal-based diet (Bark et al., 1986; Brooks and Tsourgiannis, 2003). Therefore, tremendous effort has been devoted to determining strategies to ease this transition. A popular strategy, which has shown historic success, is the inclusion of milk-based products in early nursery diets. Numerous studies have observed that feeding increased levels of milk-based products, and therefore lactose, such that inclusion of up to 30 and 15-17% lactose, from d 0-7 and 7-14 post-weaning, respectively, increases both ADFI and ADG in weanling pigs

(Mahan et al., 2004; Cromwell et al., 2008; Zhao et al., 2021). There are different sources of dietary lactose including dried whey powder, dried whey permeate, and crystalline lactose, which have all been shown to improve feed intake and growth performance. The lactose portion of these feed ingredients has been noted as the primary contributor to enhanced appetite and growth performance of nursery pigs, as crystalline lactose has been observed as a suitable substitute for dried whey (Tokach et al., 1989; Mahan 1992; Nessmith et al., 1997). Lactose is the primary sugar component of sows' milk, and as such, newly weaned pigs have high lactase activity, which makes lactose more readily digested than starch CHO's immediately after weaning (Mahan, 1992; Kim and Allee, 2001). Despite the numerous benefits observed when including sources of lactose in nursery pig diets, their relative high cost has led researchers to try to identify alternative ingredients that will elicit similar performance at lower costs.

Alternative, carbohydrate-based sugar sources have been one group of ingredients that have shown promise as potential lactose replacements in nursery diets. Many of these alternative sugar products are combinations of multiple mono- and di-saccharides, many of which (i.e., glucose, sucrose, and fructose) have been observed to be efficiently utilized as energy sources by nursery pigs (Aherne et al., 1969; Kidder and Manners, 1978; Richert et al., 1996). This is due to changes in carbohydrase concentration and activity occurring in the pigs' gastrointestinal tract during this period. While lactase is the most abundant carbohydrase at birth, the activity of lactase decreases as pigs mature, meanwhile, glucoamylase and sucrase-isomaltase activity increase (Dahlqvist, 1961; Hartman et al., 1961; Kelly et al., 1991). Kelly et al. (1991) observed that sucrase and maltase activity increased in pigs weaned at 14 d old that were continuously fed via intubation for 3 to 7 d, as well as in pigs weaned at 22 d, compared to 14 d. When the pig is approximately 4 weeks of age, sucrase-isomaltase has the greatest activity of all carbohydrases in the intestinal mucosa (Hartman et al., 1961, Kelly et al., 1991). Thus, the nursery pigs used in our experiments likely had the enzymatic capacity to utilize each of the novel CHO products studied in these experiments (CHO-D & CHO-L), which are proprietary blends of several mono- and di-saccharides which are derived from the corn wet-milling process. These products are a combination of both reducing and non-reducing sugars. Additionally, it has been observed that nursery pigs (> 21 d old) possess the enzymatic and digestive capacity to efficiently utilize each of these sugars as energy sources (Aherne et al., 1969; Kidder and Manners, 1978; Kelly et al., 1991). Moreover, this shift in carbohydrase activity is affected by substrate availability, as such the transition to a diet with reduced, or without, lactose increases the activity sucrase-isomaltase (Manners and Stevens, 1972; Yasutake et al., 1995).

Several studies have observed that traditional lactose sources can be partially, or totally, replaced with a variety of alternative sugar sources without negatively affecting feed intake or growth performance of nursery pigs (Naranjo et al., 2010; Guo et al., 2015; Dunmire et al., 2020). A study conducted by Jin et al. (1998) observed that complete replacement of crystalline lactose with sucrose supported similar ADG, ADFI and feed efficiency, while Mavromichalis et al. (2001) observed similar results when crystalline lactose was replaced by either sucrose or molasses. Moreover, multiple studies have observed that partial replacement of traditional lactose sources with combination sugar products results in comparable feed intake and growth performance (Kim and Allee, 2001; Guo et al., 2015; Dunmire et al., 2020) These results agree with those of our current study, as in Exp. 1, we observed that CHO source had no effect on any observed growth performance criteria during the experimental period, or overall. However, the results of our current study are inconclusive as we were unable to detect any differences in growth performance between pigs fed the negative control diet containing practically no lactose and the diet containing the highest level of lactose. However, the total sugar concentration used in our diets may not have been high enough to elucidate improvements in growth performance (Naranjo et al., 2010). Mahan et al., (2004) reported increasing lactose from 10 to 35% and from 7 to 31% in phases 1 and 2, respectively, linearly increased growth performance, and was maximized when feeding diets containing 25 to 30% and 17 to 22% lactose, in phase 1 and 2, respectively. In comparison, the diets used in Exp. 1 contained 5 to 10% and 2.5 to 5% lactose in phases 1 and 2, respectively. Other research has observed that including 10 to 12% lactose in the first 7 to 14 d post-weaning does not elicit increased growth performance or feed intake (Pollmann et al., 1980; Molino et al., 2011; Jeong et al., 2018). Thus, increasing the inclusion rate of the lactose and alternative CHO sources may have allowed for a greater difference in performance.

Along with providing energy substrates that match the digestive enzymes in highest concentration, a secondary purpose of including sugars in the diet of nursery pigs is to improve feed palatability after weaning and promote feed intake. Thus, an important objective of this research was to determine the effect these novel CHO products have on feed intake preference. Previous research has shown that CHOs such as sucrose and fructose enhance the appetite of nursery pigs, and pigs prefer sucrose over lactose when given the choice (Diaz et al., 1956; Glaser et al., 2000). This preference is hypothesized to be due to the increased sweetness of sucrose over lactose. Furthermore, it has been observed that inclusion of various sweeteners and sugar blend products to diets containing whey powder improved feed preference compared to diets only containing whey powder (Lewis et al., 1955; Aldinger et al., 1959; Wahlstrom et al., 1974). Moreover, when studying feed intake behavior, researchers have observed that the inclusion of high intensity artificial sweeteners increased the frequency of visits to the feeder with consumption (Maenz et al., 1993; Sterk et al., 2008). These findings support the results we observed in Exp. 2 where in phase 1, pigs tended to prefer the diet containing CHO-D over the diet containing lactose, suggesting that including CHO-D in diets may improve feed intake directly post-weaning. However, this response was inverted during phase 2, as pigs significantly preferred the diet containing lactose over CHO-D. Previous feed preference trials conducted in a similar manner to ours (Solà-Oriol et al., 2009, 2011) did not report a similar shift in dietary preferences between phases. Additionally, pigs significantly preferred the lactose-containing diet compared to the diet with the liquid CHO source in both phases. However, these results were unexpected based on previous research previously discussed.

In conclusion, pigs preferred a dry, novel CHO source in phase 1 diets compared to diets containing lactose, but in phase 2 this preference was reversed. Pigs preferred the lactose-containing diet over the CHO-L diet in all phases. When pigs were not provided with the choice of diet, feeding either of the novel CHO sources did not significantly impact growth performance, percentage of pigs that lost weight post-weaning, or fecal dry matter during the nursery period compared with those pigs fed a traditional lactose source. In this trial, the addition of lactose to the diet did not influence any response criteria compared to a diet without lactose. This response was not expected and prevented the ability to determine if either novel CHO source could replace lactose in nursery pig diets.

References

Aherne, F., V. W. Hays, R. C. Ewan, and V. C. Speer. 1969. Absorption and utilization of sugars by the baby pigs. J. Anim. Sci. 29:444-450. doi:10.2527/jas1969.293444x.

Aldinger, S. M., V. C. Speer, V. W. Hays, and D. V. Catron. 1959. Effect of saccharin on consumption of starter rations by baby pigs. J. Anim. Sci. 18:1350-1355.

Bark, L. J., T. D. Crenshaw, and V. D. Leibbrandt. 1986. The effect of meal intervals and weaning on feed intake of early weaned pigs. J. Anim. Sci. 62:1233-1239. doi:10.2527/jas1986.6251233x.

Brooks, P. H., and C. H. Tsourgiannis. 2003. Factors affecting the voluntary feed intake of the weaned pig. In: J. Le Dividich, J. R. Pluske, M. W. A. Verstegen, editor, Weaning the Pig: Concepts and Consequences. Wageningen, Netherlands: Wageningen Academic Publishers. p. 81-116.

Cromwell, G. L., G. L. Allee, and D. C. Mahan. 2008. Assessment of lactose level in the mid- to late-nursery phase on performance of weanling pigs. J. Anim. Sci. 86:127-133. doi:10.2527/jas.2006-831.

Dahlqvist, A. 1961. Intestine carbohydrase of a newborn pig. Nature. 190:31-32. doi:10.1038/190331a0.

Diaz, F., V. C. Speer, G. C. Ashton, C. H. Liu, and D. V. Catron. 1956. Comparison of refined cane sugar, invert cane molasses and unrefined cane sugar in starter rations for early weaned pigs. J. Anim. Sci. 15:315-319. doi:10.2527/jas1956.151315x.

Dunmire, K. M., T. A. Wickersham, L. L. Frenzel, S. R. Sprayberry, L. C. Joiner, L. P. Hernandez, A. M. Cassens, B. Dominguez, and C. B. Paulk. 2020. Effects of adding liquid lactose or molasses to pelleted swine diets on pellet quality and pig performance. Transl. Anim. Sci. 4:616-629. doi:10.1093/tas/txaa039.

Glaser, D., M. Wanner, J. M. Tinti, and C. Nofre. 2000. Gustatory responses of pigs to various natural and artificial compounds known to be sweet in man. Food Chem. 68:375-385.

doi:10.1016/S0308-8146(99)00212-5.

Guo, J. Y., C. E. Phillips, M. T. Coffey, and S. W. Kim. 2015. Efficacy of a supplemental candy coproduct as an alternative carbohydrate source to lactose on growth performance of newly weaned pigs in a commercial farm condition. J. Anim. Sci. 93:5304-5312. doi:10.2527/jas2015-9328.

Hartman, P. A., V. W. Hays, R. O. Baker, L. H. Neagle, and D. V. Catron. 1961. Digestive enzyme development in young pig. J. Anim. Sci. 20:114-123. doi:10.2527/jas1961.201114x

Jeong, Y. D., H. S. Ko, A. Hosseindoust, Y. H. Choi, B. J. Chae, D. J. Yu, E. S. Cho, Y. H. Kim, S. M. Shim, and C. S. Ra. 2018. Effects of dietary lactose levels and supplementation of probiotics on growth performance in weanling pigs. J. Anim. Sci. 96(Suppl. 2):42-43. doi:10.1093/jas/sky073.080.

Jin, C. F., J. H. Kim, H. K. Moon, W. T. Cho, Y. K. Han, and In K. Han. 1998. Effects of various carbohydrate sources on the growth performance and nutrient utilization in pigs weaned at 21 days of age. Asian-Aust. J. Anim. Sci. 11:285-292. doi:10.5713/ajas.1998.285.

Kidder, D. E., and M. J. Manners. 1978. Digestion of carbohydrates. Digestion in the pig. Kington Press, Bath, England. p. 96-149.

Kim, I. B., and G. L. Allee. 2001. Effect of carbohydrate sources in phase I and phase II pig starter diets. Asian-Aust. J. Anim. Sci. 14:1419-1424. doi:10.5713/ajas.2001.1419.

Kelly, D., J. A. Smyth, and K. J. McCracken. 1991. Digestive development of the early-weaned pig. 1. Effect of level of food intake on digestive enzyme activity during the first week post-weaning. Br. J. Nutr. 65:169-180. doi:10.1079/BJN19910078.

Lewis, C. J., D. V. Catron, G. E. Combs, Jr., G. C. Ashton, and C. C. Culbertson. 1955. Sugar in pig starters. J. Anim. Sci. 14:1103-1115. doi:10.2527/jas1955.1441103x.

Maenz, D. D., J. F. Patience, and M. S. Wolynetz. 1993. Effect of water sweetener on the performance of newly weaned pigs offered medicated and unmedicated feed. Can. J. Anim. Sci. 73:669-672. doi:10.4141/cjas93-073.

Mahan, D. C. 1992. Efficacy of dried whey and its lactalbumin and lactose components at two dietary lysine levels on postweaning pig performance and nitrogen balance. J. Anim. Sci. 70:2182-2187. doi:10.2527/1992.7072182x.

Mahan, D. C., N. D. Fastinger, and J. C. Peters. 2004. Effects of diet complexity and dietary lactose levels during three starter phases on postweaning pig performance. J. Anim. Sci. 82:2790-2797. doi:10.2527/2004.8292790x.

Manners, M. J., and J. A. Stevens. 1972. Changes from birth to maturity in the pattern of distribution of lactase and sucrase activity in the mucosa of small intestine in pigs. Br. J. Nutr. 28:113–127. doi:10.1079/BJN19720014.

Molino, J. P., J. L. Donzele, R. F. M. de Oliveira, A. S. Ferreira, C. A. de Moraes, D. Haese, A. Saraiva, and J. P. de Oliveira. 2011. Lactose levels in diets for piglets weaned at 21 days of age. Rev. Bras. Zootech. 40:1233-1241. doi:10.1590/S1516-35982011000600011.

Naranjo, V. D., T. D. Bidner, and L. L. Southern. 2010. Comparison of dried whey permeate and a carbohydrate product in diets for nursery pigs. J. Anim. Sci. 88:1868-1879. doi:10.2527/jas.2009-2438.

Nessmith, W. B., Jr., J. L. Nelssen, M. D. Tokach, R. D. Goodband, and J. R. Bergstrom. 1997. Effects of substituting deproteinized whey and (or) crystalline lactose for dried whey on weanling pig performance. J. Anim. Sci. 75:3222-3228. doi:10.2527/1997.75123222x.

NRC. 2012. Nutrient requirements of swine: 11th ed. Natl. Acad. Press, Washington, DC.

Wahlstrom, R. C., L. A. Hauser, and G. W. Libal. 1974. Effects of low lactose whey, skim milk and sugar on diet palatability and performance of early weaned pigs. J. Anim. Sci. 38:1267-1271. doi:10.2527/jas1974.3861267x.

Pollman, D. S., D. M. Danielson, and E. R. Peo Jr. 1980. Effect of Lactobillus spp. acidophilus on starter pigs fed a diet supplemented with lactose. J. Anim. Sci. 51:638-644. doi:10.2527/jas1980.513638x.

Richert, T. R., K. R. Cera, and A. P. Schinke. 1996. Effect of dietary carbohydrate source and level on early-weaned pigs. J. Anim. Sci. 74(Suppl. 1):169 (Abstr.)

Solà-Oriol, D., E. Roura, and D. Torrallardona. 2009. Feed preference in pigs: Effect of cereal sources at different inclusion rates. J. Anim. Sci. 87:562-570. doi:10.2527/jas.2008-0949.

Solà-Oriol, D., E. Roura, and D. Torrallardona. 2011. Feed preference in pigs: Effect of selected protein, fat, and fiber sources at different inclusion rates. J. Anim Sci. 89:3219-3227. doi:10.2527/jas.2011-3885.

Sterk, A., P. Schlegel, A. J. Mul, M. Ubbink-Blanksma, and E. M. A. M. Bruininx. 2008. Effects of sweeteners on individual feed intake characteristics and performance in group-housed weanling pigs. J. Anim. Sci. 86:2990-2997. doi:10.2527/jas.2007-0591.

Tokach, M. D., J. L. Nelssen, and G. L. Allee. 1989. Effect of protein and (or) carbohydrate fractions of dried whey on performance and nutrient digestibility of early weaned pigs. J. Anim. Sci. 67:1307-1312. doi:10.2527/jas1989.6751307x.

Tokach, M. D., J. E. Pettigrew, L. J. Johnston, M. Overland, J. W. Rust, and S. G. Cornelius. 1995. Effect of adding fat and(or) milk products to the weanling pig diet on performance in the nursery and subsequent grow-finish stages. J. Anim. Sci. 73:3358-3368. doi:10.2527/1995.73113358x.

Wensley, M. R., M. D. Tokach, J. C. Woodworth, R. D. Goodband, J. T. Gebhardt, J. M. DeRouchey, and D. McKilligan. 2021. Maintaining continuity of nutrient intake after weaning. II. Review of post-weaning strategies. Transl. Anim. Sci. 5:1-16. doi:10.1093/tas/txab022.

Yasutake, H., T. Goda, and S. Takase. 1995. Dietary regulation of sucrase-isomaltase gene expression in rate jejunum. Biochim. Biophys. Acta 1243:270–276. doi:10.1016/0304-4165(94)00143-L

Zhao, J., Z. Zhang, S. Zhang, G. Page, and N. W. Jaworski. 2021. The role of lactose in weanling pig nutrition: a literature and meta-analysis review. J. Anim. Sci. Biotechnol. 12:10. doi:10.1186/s40104-020-00522-6.

Table 5.1. Composition of phase 1 diets (as-fed basis; Exp. 1 and 2)[1]

	Dietary treatment					
Item	NC[2,3]	PC[3,4]	50% CHO-D	100% CHO-D[3]	50% CHO-L	100% CHO-L[3]
Ingredient, %						
Corn	63.27	51.68	52.32	52.93	51.54	51.40
Soybean meal (46.5% CP)	14.84	14.74	14.79	14.80	14.58	14.37
Enzymatically treated SBM[5]	5.00	5.00	5.00	5.00	4.93	4.85
Spray-dried bovine plasma	2.50	2.50	2.50	2.50	2.46	2.43
Corn DDGS	5.00	5.00	5.00	5.00	4.93	4.85
Menhaden fish meal	2.50	2.50	2.50	2.50	2.46	2.43
Whey powder, 72.9% lactose	---	13.90	6.88	---	6.77	---
CHO-D[6]	---	---	5.00	10.00	---	---
CHO-L[7]	---	---	---	---	6.41	12.62
Whey protein concentrate, 50% lactose	1.50	---	0.90	1.80	0.89	1.75
Choice white grease	1.00	1.00	1.00	1.00	0.99	0.97
Limestone	0.68	0.63	0.63	0.65	0.62	0.61
Monocalcium phosphate (21% P)	1.43	1.08	1.30	1.48	1.28	1.46
Salt	0.75	0.40	0.60	0.75	0.59	0.73
Lysine, 60%[8]	0.63	0.63	0.63	0.63	0.62	0.61
DL-Met	0.13	0.15	0.15	0.15	0.15	0.15
L-Thr	0.16	0.16	0.16	0.17	0.16	0.16
L-Trp	0.03	0.03	0.03	0.03	0.03	0.03
L-Val	0.05	0.07	0.07	0.07	0.07	0.07
Zinc oxide[9]	0.40	0.40	0.40	0.40	0.39	0.39
VTM premix[10]	0.15	0.15	0.15	0.15	0.15	0.15
Total	100	100	100	100	100	100
Calculated analysis						
Lactose, %	0.08	10.00	5.00	0.09	5.00	0.09
SID AA, %						
Lys, %	1.35	1.35	1.35	1.35	1.35	1.35
Ile:Lys	56	56	56	56	56	56
Leu:Lys	126	121	122	122	122	122
Met:Lys	33	33	34	34	34	34
Met and Cys:Lys	57	57	57	57	57	57
Thr:Lys	64	64	64	64	64	64
Trp:Lys	19.0	19.0	19.0	19.0	19.0	19.0
Val:Lys	70	70	70	70	70	70
NE, kcal/kg[11]	2,504	2,529	2,529	2,531	2,533	2,542
SID Lys:NE, g/Mcal	5.39	5.34	5.34	5.33	5.25	5.15

CP, %	21.9	21.3	21.3	21.3	21.3	21.2
Ca, %	0.71	0.70	0.70	0.71	0.70	0.70
STTD P, %	0.63	0.63	0.64	0.63	0.64	0.63
Ca:P	0.93	0.95	0.94	0.95	0.94	0.94
Na, %	0.41	0.40	0.41	0.41	0.41	0.41

---

[1] Diets were fed to pigs from approximately 6 to 7.5 kg BW in Exp. 1, and from approximately 5.5 to 8 kg BW in Exp. 2

[2] Negative control (NC) containing 0.08% lactose.

[3] The NC, PC, 100% CHO-D, and 100% CHO-L diets were used for Exp. 1 and 2.

[4] Positive control (PC) containing 10.00% lactose.

[5] HP 300; Hamlet Protein, Findlay, OH.

[6] Dry novel carbohydrate source; Cargill Starches, Sweeteners, & Texturizers, Blair, NE.

[7] Liquid novel carbohydrate source; Cargill Starches, Sweeteners, & Texturizers, Blair, NE.

[8] BioLys (Evonik Industries AG, Essen, Germany).

[9] Zinc oxide was included in the diet to provide 3,000 mg/kg of Zn.

[10] Ronozyme Hiphos (GT) 2700 (DSM Nutritional Products, Inc, Parsippany NJ), provided 1,001 phytase units (FYT/kg of the diet), for an estimated release of 0.13% STTD P.

[11] Net Energy values for novel CHO products were estimated using the EvaPig software (version 2.0.3.2; INRA, Saint-Gilles, France).

Table 5.2. Composition of phase 2 and 3 diets (as-fed basis; Exp. 1 and 2)[1]

	Dietary treatment						
Item	NC[2,3]	PC[3,4]	50% CHO-D	100% CHO-D[4]	50% CHO-L	100% CHO-L[4]	Phase 3
Ingredient, %							
Corn	59.34	53.47	53.78	54.11	53.38	53.30	64.76
Soybean meal (46.5% CP)	21.46	21.45	21.49	21.49	21.33	21.18	28.35
Corn DDGS	7.50	7.50	7.50	7.50	7.44	7.39	---
Enzymatically treated SBM[5]	5.00	5.00	5.00	5.00	4.96	4.93	---
Whey powder	---	7.00	3.44	---	3.41	---	---
CHO-D[6]	---	---	2.50	5.00	---	---	---
CHO-L[7]	---	---	---	---	3.22	6.40	---
Whey protein concentrate, 50% lactose	0.75	---	0.45	0.90	0.45	0.89	---
Choice white grease	1.00	1.00	1.00	1.00	0.99	0.99	---
Limestone	1.00	0.95	0.98	0.98	0.97	0.96	0.75
Monocalcium phosphate (21% P)	1.40	1.20	1.35	1.45	1.34	1.43	0.85
Salt	0.75	0.60	0.70	0.75	0.69	0.74	0.60
Lysine, 60%[8]	0.85	0.85	0.85	0.85	0.84	0.84	---
L-Lys HCl	---	---	---	---	---	---	0.55
DL-Met	0.18	0.19	0.19	0.19	0.19	0.19	0.21
L-Thr	0.22	0.22	0.22	0.22	0.22	0.22	0.23
L-Trp	0.04	0.04	0.04	0.04	0.04	0.04	0.05
L-Val	0.11	0.12	0.12	0.12	0.12	0.12	0.16
Zinc oxide[9]	0.25	0.25	0.25	0.25	0.25	0.25	---
VTM premix[10]	0.15	0.15	0.15	0.15	0.15	0.15	---
Vitamin premix[11]	---	---	---	---	---	---	0.25
Trace mineral premix	---	---	---	---	---	---	0.15
Total	100	100	100	100	100	100	100
Calculated analysis							
Lactose, %	0.04	5.04	2.50	0.05	2.50	0.05	0.00
SID AA, %							
Lys, %	1.35	1.35	1.35	1.35	1.35	1.35	1.30
Ile:Lys	56	56	56	56	56	56	53
Leu:Lys	122	119	119	119	119	119	111
Met:Lys	35	35	36	36	36	36	36
Met and Cys:Lys	57	57	57	57	57	57	56
Thr:Lys	64	64	64	64	64	64	63
Trp:Lys	19.0	19.0	19.0	19.0	19.0	19.0	19.3
Val:Lys	70	70	70	70	70	70	69
NE, kcal/kg[12]	2,467	2,480	2,478	2,480	2,482	2,487	2,579
SID Lys:NE, g/Mcal	5.47	5.44	5.45	5.44	5.40	5.35	5.04
CP, %	21.6	21.3	21.3	21.3	21.3	21.3	19.8

Ca, %	0.74	0.72	0.74	0.73	0.74	0.73	0.62
STTD P, %	0.57	0.57	0.57	0.57	0.57	0.57	0.44
Ca:P	1.06	1.05	1.06	1.06	1.06	1.06	1.13
Na, %	0.35	0.36	0.36	0.35	0.36	0.35	0.28

[1] Phase 2 diets were fed to pigs from approximately 7.5 to 12 kg BW, and the phase 3 diet was fed from approximately 12 to 23 kg BW. Phase 2 diets were fed to pigs from approximately 8 to 12 kg BW in Exp. 2.

[2] Negative control (NC) containing 0.04% lactose.

[3] The NC, PC, 100% CHO-D, and 100% CHO-L diets were used for Exp. 1 and 2.

[4] Positive control (PC) containing 5.04% lactose.

[5] HP 300; Hamlet Protein, Findlay, OH.

[6] Dry novel carbohydrate source; Cargill Starches, Sweeteners, & Texturizers, Blair, NE.

[7] Liquid novel carbohydrate source; Cargill Starches, Sweeteners, & Texturizers, Blair, NE.

[8] BioLys (Evonik Industries AG, Essen, Germany).

[9] Zinc oxide was included in the diet to provide 2,000 mg/kg of Zn.

[10] Ronozyme Hiphos (GT) 2700 (DSM Nutritional Products, Inc, Parsippany NJ), provided 1,001 phytase units (FYT/kg of the diet), for an estimated release of 0.13% STTD P.

[11] Ronozyme Hiphos (GT) 2700 (DSM Nutritional Products, Inc, Parsippany NJ), provided 1,250 phytase units (FYT/kg of the diet), for an estimated release of 0.13% STTD P.

[12] Net Energy values for novel CHO products were estimated using the EvaPig software (version 2.0.3.2; INRA, Saint-Gilles, France).

Table 5.3. Effects of carbohydrate source on nursery pig performance, Exp. 1[1]

	Dietary treatment[2]							
	NC	PC	50% CHO-D	100% CHO-D	50% CHO-L	100% CHO-L	SEM	*P* =[3]
Body weight, kg								
d 0	6.0	6.0	6.0	6.0	6.0	6.0	0.04	0.978
d 10	7.4	7.2	7.3	7.2	7.3	7.4	0.12	0.192
d 24	12.2	11.9	11.9	12.1	11.8	12.0	0.45	0.745
d 42	23.0	22.5	22.8	23.1	22.3	22.8	0.67	0.651
Treatment period (d 0 to 24)								
ADG, g	253	244	244	251	243	248	16.3	0.901
ADFI, g[4]	310	300	302	311	308	317	15.2	0.591
G:F, g/kg	814	812	807	805	787	778	15.7	0.058
Common period (d 24 to 42)								
ADG, g	597	588	591	609	585	600	15.2	0.756
ADFI, g	847	837	838	865	843	845	18.0	0.811
G:F, g/kg	706	704	707	703	694	711	7.5	0.726
Overall (d 0 to 42)								
ADG, g	397	390	392	402	389	399	15.1	0.869
ADFI, g[5]	534	528	529	545	538	543	15.5	0.766
G:F, g/kg	742	740	740	737	725	733	8.8	0.329
BW loss (d 0 to 7), %[6]	17.9	23.3	20.0	15.5	19.1	14.3	0.06	0.941
Fecal DM, %[7,8]								
d 10	26.4	27.3	26.9	25.7	25.4	26.3	1.00	0.718
d 24	24.1	24.4	24.3	25.3	24.1	24.3	0.94	0.699

[1] A total of 360 barrows (initial BW = 6.0 ± 0.04 kg) were used in a growth performance study with 5 pigs per pen and 12 replicates per treatment.

[2] Negative control (NC) containing 0.075 and 0.0% lactose, phase 1 and 2, respectively. Positive control (PC) containing 10 and 5% lactose, phase 1 and 2, respectively. Either 50 or 100% of lactose was replaced with a dry (CHO-D) or liquid (CHO-L) carbohydrate product on a total carbohydrate basis.

[3] Main effect of dietary treatment, tests mean separation between each dietary treatment.

[4] Throughout the treatment period (d 0 to 24) there was a weight block × CHO source interaction ($P = 0.045$) for ADFI, in which heavyweight pigs fed the PC diet containing lactose had greater ADFI than lightweight pigs fed the same diet, while there was no significant difference due to weight block among the other treatments.

[5] Overall (d 0 to 42), there was a tendency for a weight block × CHO source interaction ($P = 0.067$) for ADFI, in which heavyweight pigs fed the PC, 100% CHO-D, and 100% CHO-L diets tended to have greater ADFI than lightweight pigs fed the same diet, while there was no difference due to weight block among the other treatments.

[6] Percentage of individual pigs that lost weight from d 0 to 7 per treatment.

[7] Main effect of day was observed ($P < 0.001$).

[8] No treatment × day interaction ($P = 0.816$) was observed.

Table 5.4. Effects of carbohydrate source on feed intake preference in nursery pigs, Exp. 2[1,2]

	Dietary Treatments[3]				
	PC	CHO-D	CHO-L	SEM	*P* =
Phase 1 (d 3 to 6 and 9 to 12)					
Comparison 1[4]					
Daily feed disappearance, g[5]	520	679	---	80.3	0.170
Daily feed disappearance, %[6]	41.4	58.6	---	8.92	0.060
Comparison 2[7]					
Daily feed disappearance, g	838	---	339	64.1	< 0.001
Daily feed disappearance, %[8]	75.7	---	24.3	5.06	0.001
Phase 2 (d 17 to 20)					
Comparison 1					
Daily feed disappearance, g	1,999	885	---	197.0	0.001
Daily feed disappearance, %	69.1	30.9	---	6.85	0.001
Comparison 2					
Daily feed disappearance, g[9]	2,445	---	283	125.9	< 0.001
Daily feed disappearance, %[9]	89.3	---	10.7	4.41	< 0.001

[1] A total of 300 pigs were used in a 20-d preference trials with 5 pigs per pen and 40 or 20 replications per comparison in phase 1 and 2, respectively. Three 3-d preference periods were evaluated with the same set of 60 pens and 300 pigs per period.

[2] Feeder location within pen was balanced within each dietary comparison to minimize feeder location bias.

[3] Positive control (PC) containing 10 and 5% lactose, phase 1 and 2, respectively. Lactose was replaced with a dry (CHO-D) or liquid (CHO-L) carbohydrate product on a total carbohydrate basis.

[4] Comparison 1 compared the PC and CHO-D diets.

[5] Daily feed disappearance, g represents the average amount of feed consumed from each feeder within pen per day.

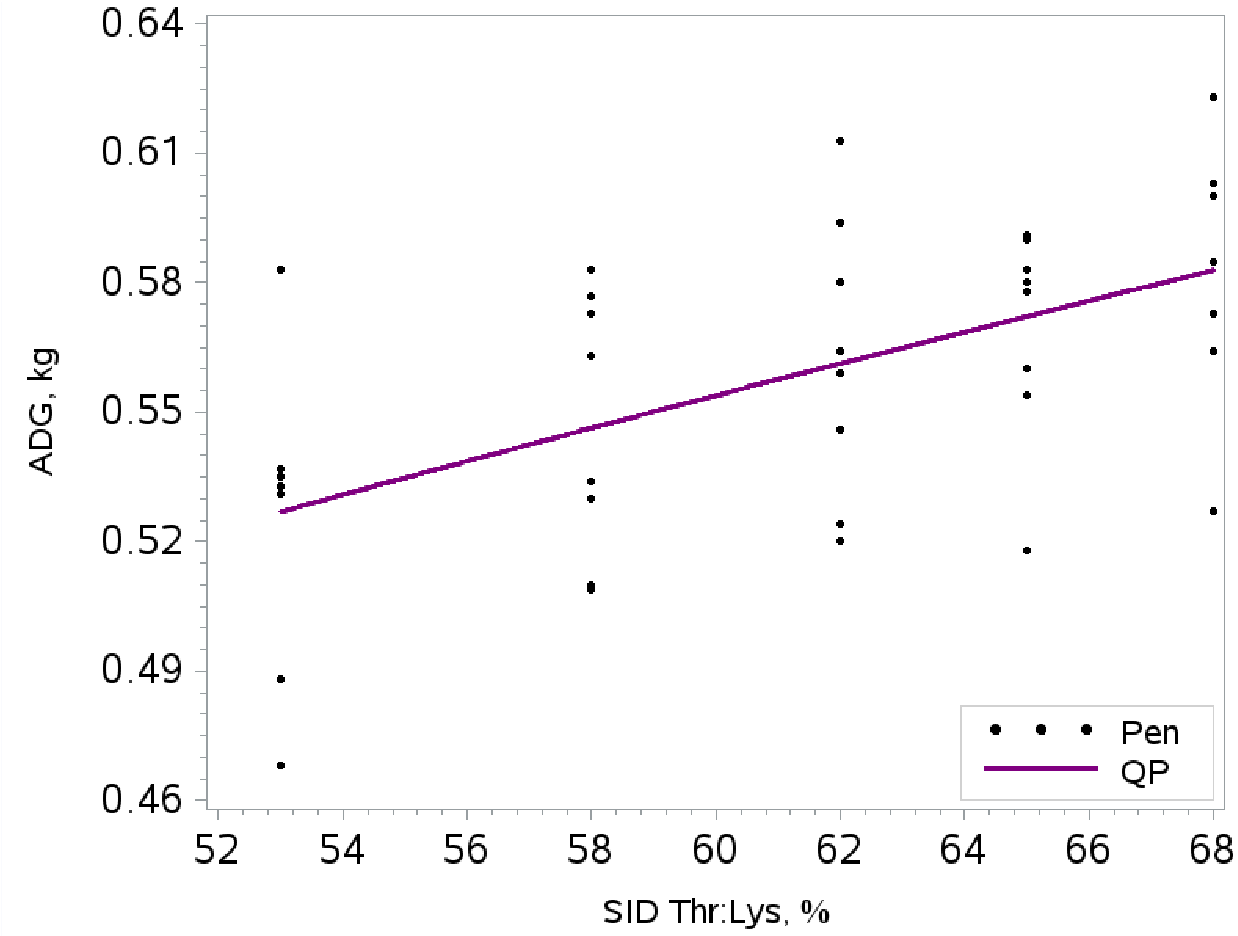
[6] Feed disappearance, % is the percentage of total feed intake for each feeder within a comparison.

[7] Comparison 2 compared the PC and CHO-L diets.

[8] Tendency (*P* = 0.073) for a weight block × diet interaction on proportion of feed intake in which lightweight pigs tended to have a greater preference for the lactose-containing diet compared to heavyweight pigs

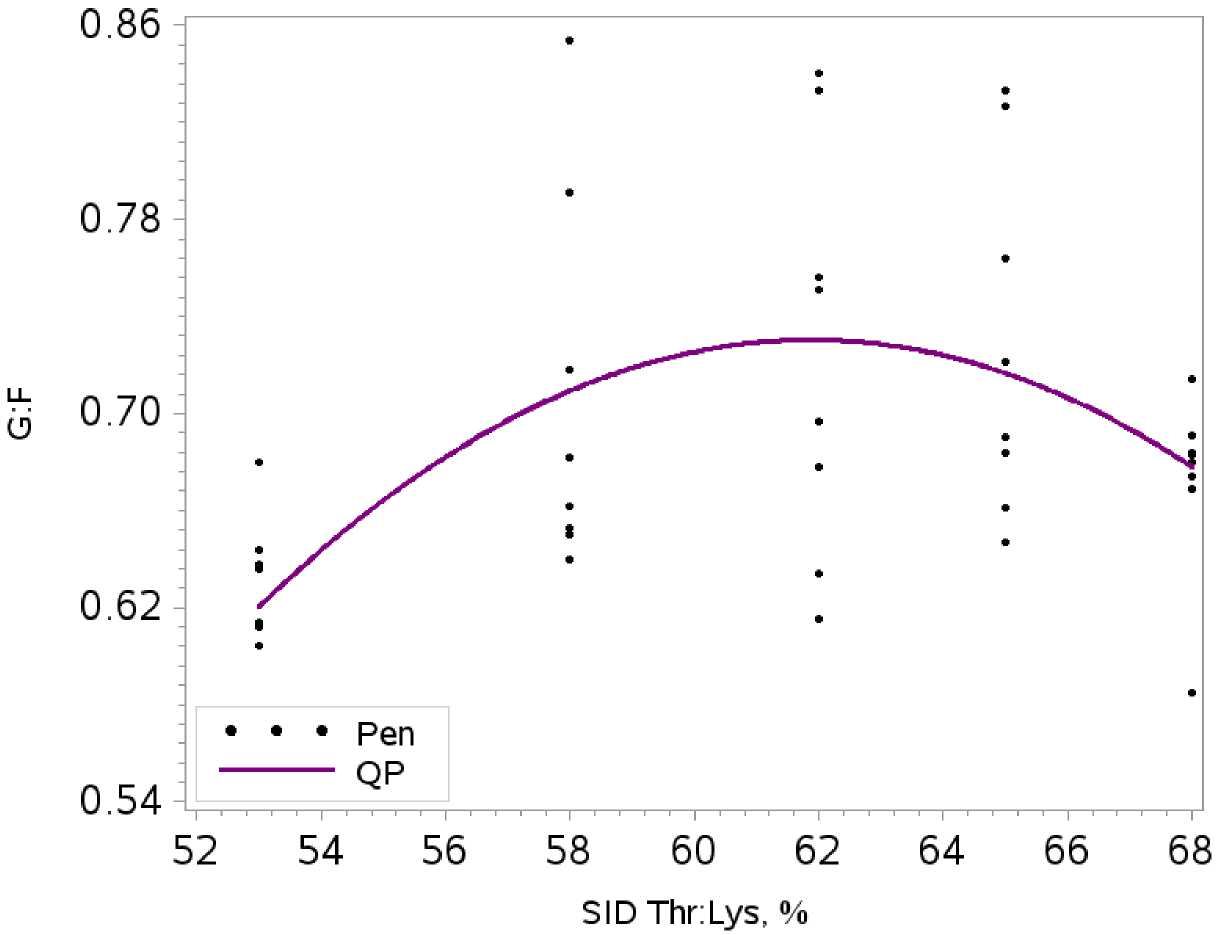
[9] Weight block × diet interaction on daily feed disappearance (*P* = 0.004) and for proportion of feed disappearance (*P* = 0.064), in which heavyweight pigs had a greater preference for the PC diet compared to the diet with CHO-L than lightweight pigs.

Appendix A - Supplemental Figures for Chapter 2



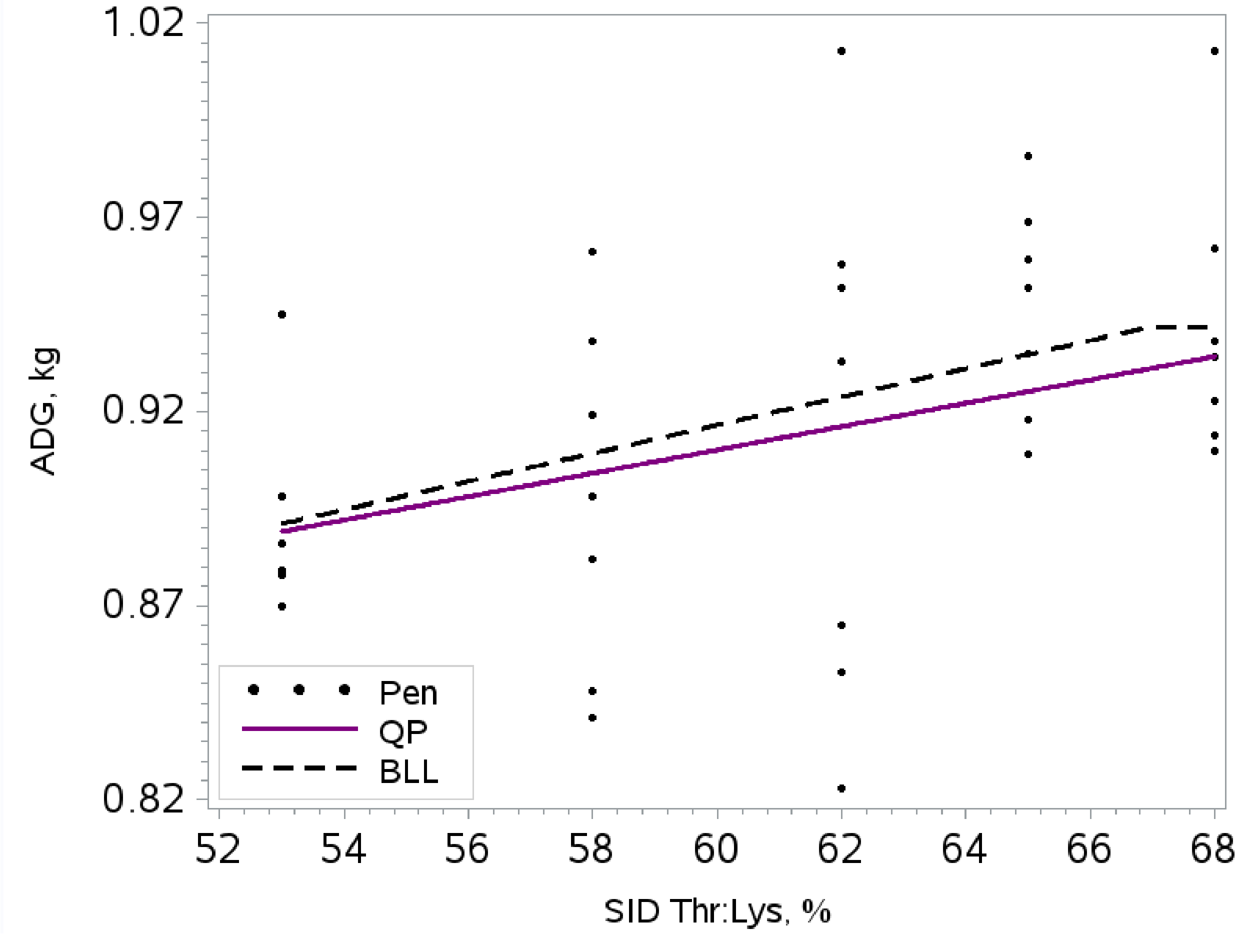
Appendix Figure A.1. Estimation of SID Thr:Lys ratio requirements to maximize ADG for 11- to 24-kg PIC 337 × 1050 pigs, Exp. 1.

A total of 987 pigs (PIC 337 × 1050; initially 11.8 ± 0.32 kg) were used in a 21-d trial. The QP model resulted in the best fit, based on BIC. The QP model predicted 95 and 100% of maximum ADG at greater than 68% SID Thr:Lys. The developed QP model equation for ADG was: ADG = -0.00002 × (SID Thr:Lys, %)^2 + 0.00556 × (SID Thr:Lys, %) + 0.2749.



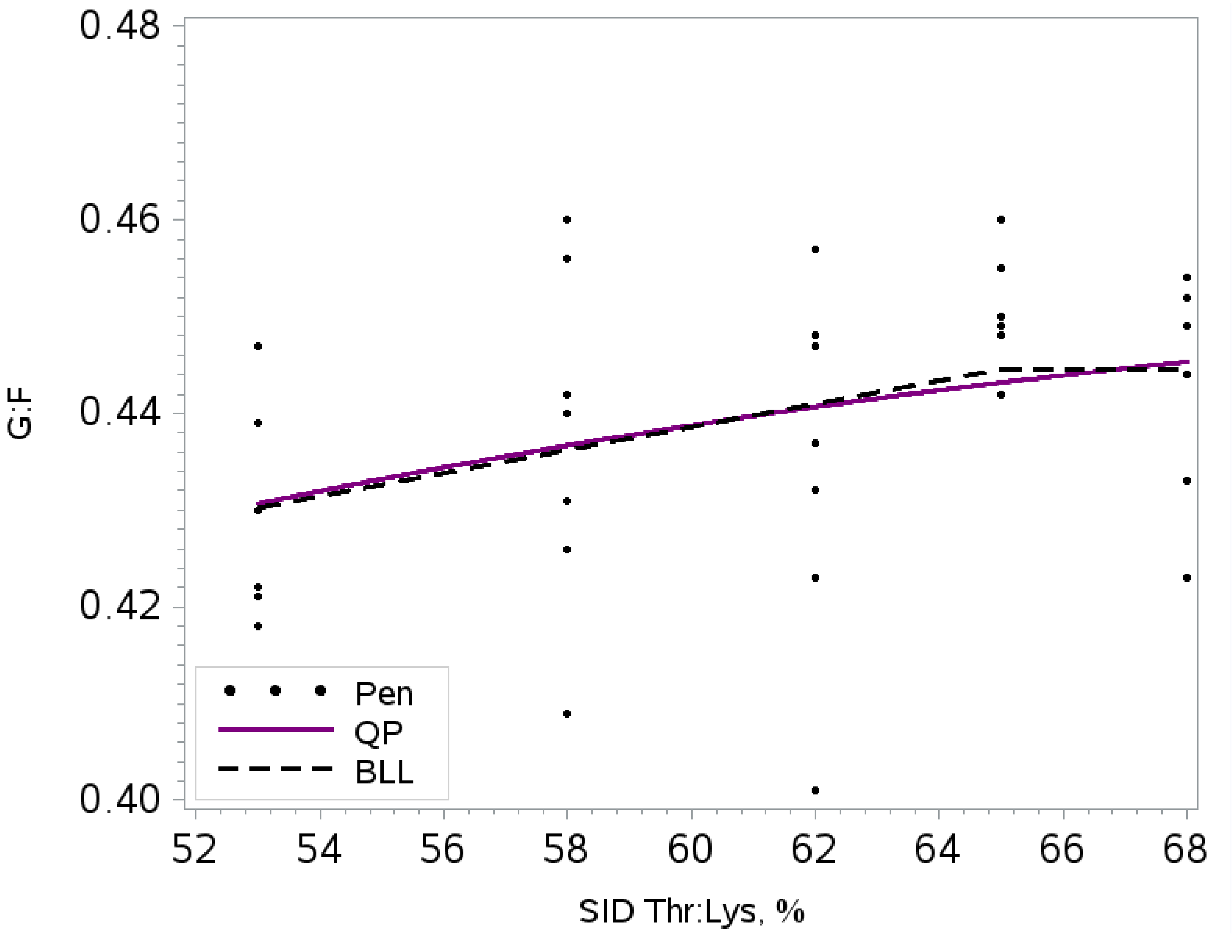
Appendix Figure A.2. Estimation of SID Thr:Lys ratio requirements to maximize G:F for 11- to 24-kg PIC 337 × 1050 pigs, Exp. 1.

A total of 987 pigs (PIC 337 × 1050; initially 11.8 ± 0.32 kg) were used in a 21-d trial. The QP model resulted in the best fit, based on BIC. The QP model predicted 95 and 100% of maximum G:F at 56.7 and 61.8% SID Thr:Lys. The developed QP model equation for G:F was: G:F = -0.0014 × (SID Thr:Lys, %)^2 – 0.1729 × (SID Thr:Lys, %) – 4.6187.



Appendix Figure A.3. Estimation of SID Thr:Lys ratio requirements to maximize ADG for 43- to 70-kg PIC 337 × 1050 pigs, Exp. 2.

A total of 875 pigs (PIC 337 × 1050; initially 43.4 ± 0.58 kg) were used in a 28-d trial. The QP and BLL models resulted in the best fit, based on BIC (BIC = -112.8 vs. -113.0, QP vs. BLL). The QP model predicted 95 and 100% of maximum ADG at greater than 68% SID Thr:Lys. The developed QP model equation for ADG was: ADG = 0.000199 × (SID Thr:Lys, %)^2 - 0.02059 × (SID Thr:Lys, %) + 1.4295. The BLL model predicted no further improvement beyond 67% SID Thr:Lys.



Appendix Figure A.4. Estimation of SID Thr:Lys ratio requirements to maximize G:F for 43- to 70-kg PIC 337 × 1050 pigs, Exp. 2.

A total of 824 pigs (PIC 337 × 1050; initially 43.4 ± 0.58 kg) were used in a 28-d trial. The QP and BLL models resulted in the best fit, based on BIC (BIC = -192.3 vs. -193.6, QP vs. BLL). The QP model predicted 95 and 100% of maximum G:F at 57.9 and greater than 68% SID Thr:Lys. The developed QP model equation for G:F was: G:F = $-0.00002 \times (\text{SID Thr:Lys, \%})^2 + 0.003684 \times (\text{SID Thr:Lys, \%}) + 0.2983$. The BLL model predicted no further improvement beyond 65% SID Thr:Lys.