Determining growing-finishing pig lysine requirements and the effects of potassium bicarbonate and crystalline lysine level on finishing pig performance

by

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Abstract

This thesis involves two studies to determine the effects of standardized ileal digestible (SID) lysine (Lys) requirements of growing-finishing pigs from 18 to 128 kg of body weight (BW) as well as evaluating the effects of adding potassium bicarbonate ($KHCO_3$) to diets with high or low crystalline lysine (L-Lys HCl) to influence dietary cation-anion difference (DCAD). Five experiments involving 2,903 pigs were conducted to determine the SID Lys requirement for maximum growth and economic return at five weight ranges throughout the growing and finishing phases. Using this data, we were able to create a pair of quadratic equations to estimate the SID Lys to Net Energy (NE) ratio required to achieve maximum growth potential and economic return throughout the growing-finishing phase. the quadratic equation of Lys:calorie ratio, g of SID Lys/Mcal of NE = 0.0002611 × BW^2, in kg – 0.0711037 × BW, in kg, + 7.284 was developed to reflect requirement for maximal growth performance from 18 to 128 kg BW. Optimal IOFC is best described by the quadratic equation: Lys:calorie ratio, g of SID Lys/Mcal of NE = 0.0001558 × BW^2, in kg, - 0.04030769 × BW + 5.410. Additionally, these results suggest that the most economical SID Lys level from 18 to 100 kg is below that for maximal growth rate. However, in 103 to 128 kg pigs, the SID Lys requirements for maximum growth performance and economic return are much more closely aligned. A second project utilized 1,944 pigs to determine if balancing DCAD levels, via added $KHCO_3$, in diets containing low or high levels of L-Lys HCl influences finishing pig growth performance or carcass characteristics. Dietary cation-anion difference is a measure of the level of monovalent ions (Na^+, K^+, and Cl^-) within the diet, which correlates to the acid-base balance within the animal. Extreme DCAD

levels, both high and low, have been shown to negatively impact feed intake and growth in pigs, previous research shows that a wide range may optimize performance.

Table of Contents

List of Figures

List of Tables

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Chapter 1 - Effects of standardized ileal digestible lysine level on growth performance and economic return for 18 to 128 kg Duroc-sired pigs

Abstract

The recent shift of the U.S. swine industry towards improved pork quality has led to increased use of Duroc-sired pigs in the marketplace. Our objective was to determine the standardized ileal digestible (SID) Lys requirement estimates for Duroc-sired (600 × 241, DNA, Columbus NE) pigs from 18 to 128 kg BW. We conducted a series of experiments using corn-soybean meal-based diets with pigs allotted to 6 or 7 treatments in randomized complete block designs. In Exp. 1, 300 pigs (initially 18.4 ± 0.50 kg) were used with 5 pigs per pen and 10 pens per treatment with 6 SID Lys levels from 1.00 to 1.50%. Increasing SID Lys increased (linear, $P < 0.040$) final BW, ADG, G:F, and Lys intake/kg of gain, and decreased (linear, $P = 0.012$) ADFI. In Exp. 2, 608 pigs (initially 36.3 ± 0.91 kg) were used with 7 to 9 pigs per pen and 12 pens per treatment with 6 SID Lys levels from 0.80 to 1.20%. Increasing SID Lys increased (linear, $P \leq 0.036$) ADG, G:F, and Lys intake/kg of gain. In Exp. 3, 700 pigs (initially 53.2 ± 0.86 kg) were used with 8 to 10 pigs per pen and 12 pens per treatment with 6 SID Lys levels from 0.65 to 1.00%. Increasing SID Lys increased (linear, $P < 0.001$) final BW, ADG, and Lys intake/kg of gain, decreased (quadratic, $P = 0.004$) ADFI, and improved (quadratic, $P < 0.001$) G:F. In Exp. 4, 616 pigs (initially 76.4 ± 1.25 kg) were used with 8 to 10 pigs per pen and 5, 6, or 11 pens per treatment with 7 SID Lys levels from 0.58 to 1.00%. Increasing SID Lys increased (linear, $P \leq 0.022$) ADG, Lys intake/kg of gain, and G:F. In Exp. 5, 679 pigs (initially 103.8 ± 1.32 kg) were used with 8 to 10 pigs per pen and 11 or 12 pens per treatment with 6 SID Lys levels from 0.43 to 0.78%. Increasing SID Lys increased (linear, $P \leq 0.043$) final BW, ADG, and Lys intake/kg of gain, and improved (quadratic, $P \leq 0.032$) G:F. Using results from all experiments, the quadratic equation of Lys:calorie ratio, g of SID Lys/Mcal of NE = $0.0002611 \times BW^2 – 0.0711037 \times BW + 7.284$ was developed to reflect the requirement for maximal growth performance from 18 to 128 kg BW. Maximal income over feed cost (IOFC) is best described by the quadratic equation: Lys:calorie ratio, g of SID Lys/Mcal of NE = $0.0001558 \times BW^2 - 0.04030769 \times BW + 5.410$. These data provide updated SID Lys estimates for Duroc sired grow-finish pigs.

Key Words: Amino acid, economics, growth, grow-finish pig, lysine

Introduction

Improvements in modern swine genetics have resulted in an increased potential for growth performance and protein accretion, which may cause a shift in dietary nutrient requirements. As a result, it is important to continuously analyze and reassess dietary nutrient requirements (O'Connell et al., 2006). Lysine is typically the first limiting amino acid in corn-soybean meal-based swine diets, and as such an accurate estimation of Lys requirements is crucial to maximize lean growth while optimizing feed cost in growing-finishing pigs. Numerous factors have an impact on Lys requirements, such as genetics, environmental conditions, sex, and pig body weight (Campbell and Taverner, 1988). Genetic suppliers provide estimates for amino acid requirements; however, validating these levels is necessary to optimize growth performance and economic returns (De La Llata et al., 2001; Main et al., 2008, Shelton et al., 2011). Additionally, it is important to have an appreciation for the biological and economic implications of feeding below, at, or above biological requirements throughout the grower-finishing period when developing feeding regimens (Main et al., 2008).

Recently, the U. S. swine industry has shifted towards an emphasis for improved pork quality, which has led to increased usage of Duroc-sired pigs in the marketplace. Suzuki et al. (2003) observed that Duroc-sired pigs had excellent growth rates and intramuscular fat content. Moreover, Soto et al. (2019) observed that Duroc-sired late finishing pigs had 6% greater overall feed intake compared with Pietrain-influence sired pigs reported by Gonçalves et al. (2017). Therefore, the objective of these experiments was to determine the standardized ileal digestible (SID) Lys estimates for Duroc sired finishing pigs from 18 to 128 kg with the intent of developing a SID Lys requirement estimate curve for this genotype.

Materials and Methods

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in these experiments. All experiments were conducted at 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 a nipple waterer. Pens were located over a metal tri-bar floor with a 1.21-m pit underneath for manure storage. In Exp. 2, 3, 4, and 5, each pen was equipped with a 2-hole dry, single-sided feeder (Farmweld, Teutopolis, IL) and a 1-cup waterer, and adjustable gates to allow 0.74 m^2 per pig. Pens were located over a completely slatted concrete floor with a 1.21-m pit underneath for manure storage. A robotic feeding system (FeedPro; Feedlogic Corp., Wimar, MN) was used to deliver and record daily feed additions to each individual pen. Pigs were provided *ad libitum* access to water and feed in meal form throughout the experiments. Complete diets were manufactured at Hubbard Feeds, Beloit, KS for each experiment. All experimental diets were corn-soybean meal-based. In Exp. 2, 3, 4, and 5, two diets were formulated to 0.80 and 1.20, 0.65 and 1.00, 0.58 and 1.00, and 0.43 and 0.78% SID Lys, respectively. These dietary treatments were blended via a robotic feeding system to establish the range of SID Lys levels in each experiment (Tables 1.2 and 1.3).

In each experiment, Duroc-sired pigs (600× 241, DNA, Columbus NE) were used to estimate the SID Lys requirement. For all experiments, ratios of other AAs to Lys were maintained well above requirement estimates to ensure that Lys was the first-limiting AA. Although the increase in dietary Lys was brought about by increasing the ratio of soybean meal to corn which also increased the CP content of the diet, Lys was the first limiting AA. This formulation strategy was used to make the results more translational to application, as SID Lys is typically increased within the industry by increasing both soybean mean and L-Lys HCl. Previous research by Yen et al. (2005), Main et al. (2008), and many others have employed a similar diet formulation strategy in determining Lys requirements of finishing pigs. In all experiments, pens of pigs were weighed, and feed disappearance was recorded approximately every 7 d to determine ADG, ADFI, and G:F in all experiments.

Experiment 1

A total of 300 pigs (initially 18.4 ± 0.50 kg to approximately 40 kg) were used in a 24-d study. There were 5 mixed-gender pigs per pen at a floor space of 0.30 m^2 per pig. Pens of pigs were allotted by BW and randomly assigned to 1 of 6 dietary treatments with 10 replications per treatment in a randomized complete block design (RCBD). Dietary treatments were corn-soybean meal based and formulated to 1.00, 1.10, 1.20, 1.30, 1.40, or 1.50% SID Lys containing

0.25, 0.30, 0.35, 0.40, 0.45, and 0.50% L-Lys HCl, respectively, with other feed-grade AAs added as necessary to maintain ratios relative to Lys (Table 1.1).

Experiment 2

A total of 608 pigs (initially 36.3 ± 0.91 kg to approximately 54 kg) were used in two separate groups lasting 14- and 21-d, respectively. There were 7 to 9 mixed gender pigs per pen at a floor space of 0.74 m^2 per pig. Pigs were allotted by BW and randomly assigned to 1 of 6 dietary treatments in a RCBD. The dietary treatments included 6 SID Lys concentrations (0.80, 0.88, 0.96, 1.04, 1.12 and 1.20%), with 12 replications per treatment.

Experiment 3

A total of 700 pigs (initially 53.2 ± 0.86 kg to approximately 75 kg) were used in two separate studies, each lasting 21-d. There were 8 to 10 pigs per pen with similar numbers of barrows and gilts in each pen. Pens of pigs were allotted by BW and randomly assigned to 1 of 6 dietary treatments in a RCBD. The dietary treatments included 6 SID Lys concentrations (0.65, 0.72, 0.79, 0.86, 0.93, and 1.00%), with 12 replications per treatment.

Experiment 4

A total of 616 pigs (initially 76.4 ± 1.25 kg to approximately 106 kg) were used in two separate studies, each lasting 21-d. There were 8 to 10 mixed gender pigs per pen with similar numbers of barrows and gilts placed in each pen. Pens of pigs were allotted by BW and randomly assigned to 1 of 7 dietary treatments in a RCBD. The dietary treatments included 7 SID Lys concentrations (0.58, 0.65, 0.72, 0.79, 0.86, 0.92, and 1.00%), with 11 replications for the 0.65, 0.72, 0.79, 0.86, and 0.92% SID Lys treatments; 6 replications for the 0.58% SID Lys treatment; and 5 replications for the 1.00% SID Lys treatment.

Experiment 5

A total of 679 pigs (initially 103.8 ± 1.32 kg to approximately 128 kg) were used in two separate studies, lasting 21- and 28-d. There were 8 to 10 mixed gender pigs per pen with similar numbers of barrows and gilts placed in each pen. Pens of pigs were allotted by BW and randomly assigned to 1 of 6 dietary treatments in a RCBD. The dietary treatments included 6 SID Lys concentrations (0.43, 0.50, 0.57, 0.64, 0.71, and 0.78%), with 12 replications for the 0.43, 0.50, 0.57, 0.71, and 0.78% SID Lys treatments, and 11 replications for the 0.64% SID Lys treatment.

Chemical analysis

A sample of each diet in Exp. 1 and from the lowest and highest SID Lys, % diets in Exp. 2, 3, 4, and 5 was submitted for AA profile (Tables 1.4 and 1.5). In experiment 1, representative diet samples were obtained from every third bag of feed. In experiments 2, 3, 4, and 5, diet samples were taken from 6 feeders per dietary treatment 3 d after the beginning of each trial. Diet samples were stored at -20°C until they were homogenized, subsampled, and submitted for analysis of AA profile (method 994.12; AOAC International, 2012) conducted by Ajinomoto Animal Nutrition North America, Inc. (Eddyville, IA).

Economic analysis

For the economic analysis, feed cost/pig, feed cost/kg gain, revenue per pig, and IOFC were calculated for high- and low-priced diets. High-priced diet costs were determined using the following ingredient prices: corn = $6.00/bushel ($236/tonne); soybean meal = $440/tonne; L-Lys at $1.76/kg; DL-Met at $5.51/kg; L-Thr at $2.65/kg; L-Trp at $11.02/kg; and L-Val at $8.82/kg. Low-priced diet costs were determined using the following ingredient prices: corn = $3.00/bushel ($118/tonne); soybean meal = $330/tonne; L-Lys at $1.43/kg; DL-Met at $3.75/kg;

L-Thr at \$1.87/kg; L-Trp at \$6.61/kg; and L-Val at \$5.51/kg. Feed cost/pig was determined by total feed intake × diet cost (\$/kg). Feed cost/kg of gain was calculated using feed cost/pig divided by total gain. Revenue per pig was determined for both a high- and a low-price by total gain × \$1.46/kg live gain, or total gain × \$0.99/kg live gain, respectively. Income over feed cost was calculated using revenue/pig – feed cost/pig.

Statistical analysis

Data were analyzed as a RCBD for a one-way ANOVA using the lmer function from the lme4 package in R Studio (Version 3.5.2, R Core Team; Vienna, Austria) with pen serving as the experimental unit, pen average BW as blocking factor, and treatment as fixed effect. Dose response curves were evaluated using linear (LM), quadratic polynomial (QP), and broken-line linear (BLL) models. For each response variable, the best-fitting model was selected using the Bayesian Information Criterion (BIC). A decrease in BIC greater than 2.0 among models for a particular response criterion was considered an improved fit. Results were considered significant with $P \leq 0.05$ and were considered marginally significant with $P \leq 0.10$. The predicted requirement for maximum growth performance and economic return found from dose response curves in each study were used to develop regression equations to predict the overall Lys:calorie ratio required for maximum growth performance and economic return. For economic return, the highest breakpoint suggested by the dose response models was used to develop the regression equation. These curves describe the Lys:calorie ratio that best met biological requirements for growth performance and optimized IOFC in this series of trials (Figure 1.6).

Results

Experiment 1

In 18- to 40-kg pigs, increasing SID Lys increased d 24 BW (linear, $P \leq 0.04$; Table 1.6). Overall ADG increased with increasing SID Lys (linear, $P = 0.003$). Pigs fed increasing SID Lys had decreased (linear, $P = 0.012$) ADFI from d 0 to 24. An improvement for overall G:F (linear, $P < 0.001$) was observed with increasing SID Lys. Daily SID Lys intake and Lys intake per kg of gain increased (linear, $P < 0.001$) with increasing SID Lys. For economic analysis, feed cost and feed cost per kg of gain increased (linear, $P < 0.001$), while total revenue tended to decrease (linear, $P = 0.074$) with increasing SID Lys at both high and low ingredient and pig prices. At high ingredient and pig prices, there was no evidence of significant difference ($P > 0.10$) for IOFC. However, at low ingredient and pig prices, increasing SID Lys decreased (linear, $P = 0.048$) IOFC, with pigs fed diets containing 1.10% SID Lys having the greatest numeric IOFC.

Dose response curves were evaluated for overall growth performance, and when modeling ADG, the LM and QP models resulted in a comparable fit. The QP model equation was: ADG = $-0.282148 \times (\text{SID Lys, \%})^2 + 0.797053 \times (\text{SID Lys, \%}) + 0.339$, with maximum ADG estimated at 1.41% SID Lys (Figure 1.1A). For the LM, maximum ADG was predicted above 1.50% SID Lys. For G:F, the LM resulted in the best fit, and predicted maximum feed efficiency above 1.50% SID Lys (Figure 1.1B).

When modelling IOFC at high ingredient and pig prices, the LM model resulted in the best fit and predicted the SID Lys requirement to achieve maximum IOFC was at less than 1.00% (Figure 1.1C). Meanwhile, at low ingredient and pig prices, the LM and BLL models had a similar fit to maximize IOFC. The LM estimated maximum IOFC at less than 1.00% SID Lys, while the BLL model predicted similar IOFC from 1.00 to 1.12% SID Lys with a reduction in IOFC when SID Lys increased past 1.12% (Figure 1.1D).

Experiment 2

In 36- to 54-kg pigs, increasing SID Lys did not significantly affect ($P > 0.10$) final BW (Table 1.7). However, ADG increased (linear, $P = 0.036$) with increasing SID Lys, while there was no observed difference ($P > 0.10$) in ADFI. As a result, increasing SID Lys increased (linear, $P < 0.001$) G:F. Daily SID Lys intake and Lys intake per kg of gain increased (linear, $P < 0.001$) with increasing SID Lys.

For economic analysis, feed cost and feed cost per kg of gain increased (linear, $P < 0.002$), and revenue tended to increase (linear, $P = 0.060$) with increasing SID Lys at both high and low ingredient and pig prices. At high ingredient and pig prices, there was no evidence of difference ($P > 0.10$) for IOFC. However, at low ingredient and pig prices, increasing SID Lys tended to decrease (linear, $P = 0.097$) IOFC, with pigs fed diets containing 0.88 or 0.96% SID Lys having the greatest numeric IOFC.

Dose response curves for overall growth performance revealed that LMs were the best fit for ADG and G:F, with the SID Lys requirement to maximize ADG and G:F predicted above 1.20% (Figure 1.2A and 1.2B). At both high and low ingredient and pig prices, LMs resulted in the best fit for IOFC, with maximum IOFC estimated at less than 0.80% SID Lys (Figure 1.2C and 1.2D).

Experiment 3

In 53- to 75-kg pigs, increasing SID Lys increased (linear, $P < 0.001$) final BW (Table 1.8). Average daily gain increased (linear, $P < 0.001$) with increasing SID Lys while for ADFI, there was a quadratic ($P = 0.004$) decrease with increasing SID Lys. A linear and quadratic ($P <$

0.001) response was observed for overall G:F with increasing SID Lys. Additionally, daily SID Lys intake and Lys intake per kg of gain increased (linear and quadratic, $P < 0.003$) with increasing SID Lys.

For economic analysis, feed cost increased (linear and quadratic, $P < 0.023$), while feed cost per kg of gain decreased (linear and quadratic, $P < 0.012$) with increasing SID Lys in both economic scenarios. Meanwhile, at both high and low ingredient and pig prices, increasing SID Lys increased linearly ($P < 0.002$) revenue and IOFC.

Dose response curves were evaluated for overall growth performance with the LM being the best fitting model for ADG, predicting maximum ADG above 1.00% SID Lys (Figure 1.3A). The QP model resulted in the best fit to optimize feed efficiency. The QP model equation was: G:F = $-0.4830938 \times (\text{SID Lys, \%})^2 + 0.9555893 \times (\text{SID Lys, \%}) - 0.027$ with maximal G:F estimated at 0.99% SID Lys (Figure 1.3B). When modelling IOFC at high ingredient and pig prices, the BLL model resulted in the best fit, predicting no further improvement in IOFC past 0.76% SID Lys (Figure 1.3C). Meanwhile, at low ingredient and pig prices, the LM and QP models had a comparable fit. The LM predicted maximum IOFC above 1.00% SID Lys. The QP model equation was: IOFC = $-14.5626 \times (\text{SID Lys, \%})^2 + 26.6348 \times (\text{SID Lys, \%}) -0.085$, with maximum IOFC estimated at 0.91% SID Lys (Figure 1.3D).

Experiment 4

In 76- to 100-kg pigs, increasing SID Lys did not significantly affect ($P > 0.10$) final BW (Table 1.9). Average daily gain increased (linear, $P = 0.022$) with increasing SID Lys, while there was no observed difference ($P > 0.10$) in ADFI. As a result, increasing SID Lys increased (linear, $P < 0.001$) G:F, with pigs fed diets containing 0.86% SID Lys having the greatest numeric G:F. Daily SID Lys intake and Lys intake per kg of gain increased (linear, $P < 0.001$)

with increasing SID Lys. For economic analysis, feed cost increased (linear, $P < 0.001$), and feed cost per kg of gain increased (linear and quadratic, $P < 0.041$) with increasing SID Lys in both pricing scenarios. Increasing SID Lys tended to increase (linear, $P = 0.051$) revenue at both high and low ingredient and pig prices. For IOFC, increasing SID Lys did not have a significant effect ($P > 0.10$) in either pricing scenario, however, pigs fed diets containing 0.65 or 0.72% SID Lys had the greatest numeric IOFC.

When modeling dose response curves for ADG, the BLL and LM models resulted in a comparable fit. The BLL model predicted no further improvement in ADG above 0.83% SID Lys, while the LM estimated maximum ADG above 1.00% (Figure 1.4A). For G:F, the LM and QP models resulted in a comparable fit, with the LM predicting maximum G:F at greater that 1.00% SID Lys. The QP equation model was: G:F = $-0.2244707 \times (\text{SID Lys, \%})^2 + 0.4156878 \times (\text{SID Lys, \%}) + 0.190$, with 100% of maximum G:F estimated at 0.93% SID Lys (Figure 1.4B). When modelling IOFC at high ingredient and pig prices, the QP was the best fitting model. The QP model equation was: IOFC = $-17.3293 \times (\text{SID Lys, \%})^2 + 27.0408 \times (\text{SID Lys, \%}) + 4.169$, with maximum IOFC estimated at 0.78% SID Lys (Figure 1.4C). However, at low ingredient and pig prices, the BLL and LM models resulted in a comparable fit. The BLL model predicted a reduction in IOFC when SID Lys increased past 0.76%, while the LM model estimated maximum IOFC at less than 0.58% SID Lys (Figure 1.4D).

Experiment 5

In 103- to 128-kg pigs, increasing SID Lys increased (linear, $P = 0.025$) final BW, with pigs fed diets containing 0.71% SID Lys having the greatest numeric BW (Table 1.10). Average daily gain increased linearly ($P = 0.043$) with increasing SID Lys, while there was no observed difference ($P > 0.10$) in ADFI. As a result, increasing SID Lys increased (linear and quadratic, *P*

< 0.032) G:F, with pigs fed diets containing 0.71% SID Lys having the greatest numeric G:F. Daily SID Lys intake and Lys intake per kilogram of gain increased (linear, $P < 0.001$) with increasing SID Lys.

For economic analysis, at high ingredient and pig prices there was no significant difference between treatments for feed cost per pig ($P > 0.10$). However, at low ingredient and pig prices, increasing SID Lys increased (linear, $P = 0.014$) feed cost per pig. At high prices, increasing SID Lys had a quadratic effect ($P = 0.032$) on feed cost per kg of gain. Meanwhile at low ingredient and pig prices, increasing SID Lys increased (linear, $P = 0.044$) feed cost per kg of gain. In both economic scenarios, increasing SID Lys increased (linear, $P = 0.028$) revenue. At high ingredient and pig prices, IOFC increased (linear and quadratic, $P < 0.020$) with increasing SID Lys. Additionally, increasing SID Lys had a quadratic effect ($P = 0.004$) on IOFC at low ingredient and pig prices, with pigs fed diets containing 0.71% SID Lys having the greatest numeric IOFC in each scenario.

When modelling dose response curves for ADG and G:F, BLL models resulted in the best fit. The BLL model for maximum ADG predicted no further improvement past 0.64% SID Lys (Figure 1.5A). Meanwhile, the BLL model for maximum G:F estimated no further improvement above 0.59% SID Lys (Figure 1.5B). When modelling IOFC at high or low ingredient and pig prices, the QP model resulted in the best fit. At high ingredient and pig prices the QP model equation was: $\text{IOFC} = -42.6028 \times (\text{SID Lys, \%})^2 + 54.9097 \times (\text{SID Lys, \%}) - 4.047$, with maximum IOFC predicted at 0.64% SID Lys (Figure 1.5C). Additionally, at low ingredient ant pig prices, the QP model equation was: $\text{IOFC} = -25.9430 \times (\text{SID Lys, \%})^2 + 32.4160 \times (\text{SID Lys, \%}) + 0.901$, with maximum IOFC estimated at 0.62% SID Lys (Figure 1.5D).

Prediction Equations

A summary of the optimum Lys:calorie ratio observed in each trial as well as the associated SID Lys intake per day and per kg of gain are provided in Table 1.11. These values were used to develop regression equations to predict the Lys:calorie ratio required for maximum growth performance and IOFC of 18- to 128-kg pigs (Figure 1.6). To maximize growth performance, the quadratic equation of Lys:calorie ratio, g of SID Lys/Mcal of NE = $0.0002611 \times BW^2 - 0.0711037 \times BW + 7.284$ was developed. To optimize IOFC, the quadratic equation of Lys:calorie ratio, g of SID Lys/Mcal of NE = $0.0001558 \times BW^2 - 0.04030769 \times BW + 5.410$ was developed.

Discussion

Essential AA requirements for growing-finishing pigs are commonly based on ratios to Lys. As a result, it is critical to have an accurate estimation of Lys requirements to maximize growth performance and optimize feed cost throughout the growing-finishing period (Soto et al., 2019). Moreover, continuous advancements in modern pig genetics have led to increased potential for growth performance and protein accretion, potentially leading to increased dietary nutrient requirements (O'Connell et al., 2006). Additionally, advancements in dose-response models have provided a strategy to estimate nutrient requirements more accurately (Gonçalves et al., 2016). This trend in genetic improvement, coupled with technological improvements to help optimize health status, environmental conditions, and management plans, has allowed for improvements in growth performance and carcass composition. Between 1980 and 2019, the average market weight of pigs has increased by 18 kg (National Pork Board, 2016; 2020). Coupled with this increased market weight, pigs have become more efficient. Between 1990 and

2019 average growth rate of wean-to-finish pigs increased from 0.58 to 0.80 kg/day, while feed intake per kg of gain decreased from 3.2 to 2.6 kg during that same time frame (PigChamp, 1990; National Pork Board, 2020). Similarly, this improved growth performance was observed in our study, as pigs grew at an average between 0.89 and 1.08 kg/day across our 5 experiments.

Estimations of dietary Lys requirements for growing-finishing pigs have changed considerably in the last 30 years. Cromwell et al. (1993) suggested that the total Lys requirement for barrows and gilts from 35 to 105 kg was 0.60 and 0.90%, respectively. Hahn et al. (1995) suggested a total Lys requirement for barrows and gilts weighing between 90 and 110 kg of 0.49 and 0.52%, respectively. More recently, in a meta-analysis with PIC (Hendersonville, TN) genetic lines, Gonçalves et al. (2017) suggested that the SID Lys requirement for barrows and gilts was 1.11 and 1.16% (25 to 50 kg), 0.91 and 0.94% (50- to 75-kg), 0.78 and 0.80% (75- to 100-kg), and 0.70 and 0.75% (100 to 135 kg), respectively. Soto et al. (2019) observed that late finishing pigs (102- to 128-kg) grown in the same facilities with similar genetic maternal and paternal lines as our study achieved maximum ADG and G:F at 0.62 and 0.63% SID Lys, respectively. In our study, the SID Lys estimate for maximum growth performance was 1.41 to 1.50%, 1.20%, 0.99 to 1.00%, 0.83 to 0.93%, and 0.59 to 0.64% for pigs weighing 18 to 40 kg, 36 to 54 kg, 53 to 75 kg, 76 to 100 kg, and 103 to 128 kg, respectively.

During the grower period (25 to 50 kg) we observed considerably higher estimates than those of Gonçalves et al. (2017). This difference may be a result of drastic differences in daily feed intake (2.31 kg/day in Gonçalves vs. 1.99 kg/day in current study). Pigs in our study may have required a considerably higher SID Lys percentage in the diet to meet a similar Lys intake per kg of gain. Similarly, in pigs weighing between 50 and 100 kg, we observed higher lysine requirements than those of Gonçalves et al. (2017). In late finishing (103 to 128 kg pigs), we observed a similar SID Lys requirement to those of Soto et al. (2019), which was considerably lower than those of Gonçalves et al. (2017).

Variation in Lys requirements could be attributable to differences in genetic capability for protein deposition, amino acid digestibility, or immune stress (Kendall et al., 2007). Lysine requirements are often expressed as a function of SID Lys required per kg of BW gain. Our estimated requirement ranged from approximately 22.6 to 23.3 g SID Lys/kg gain for 18 to 75 kg pigs and from 21.3 to 22.5 g SID Lys/kg gain for 76 to 128 kg pigs. In comparison, Shelton et al. (2011) and Main et al. (2008) observed a requirement ranging between 19.6 and 23.0 g SID Lys/kg gain in pigs weighing 35 to 110 kg. Additionally, Main et al. (2008) and Soto et al. (2019) observed a requirement ranging between 17.0 and 22.6 g SID Lys/kg gain in pigs weighing 100 to 130 kg. The increased requirement of SID Lys intake per kg of BW gain observed in our trials may be a result of pigs depositing a higher proportion of protein rather than lipids compared to previous research.

Economic analysis, as well as growth performance, is vital when developing nutritional programs. Income over feed cost accounts for the gross sale revenue and feed expense generated. Multiple studies have observed that nutrient requirements to maximize biological performance may align with optimal IOFC estimates (De La Llata et al., 2001; Main et al., 2008). In contrast, our results in Exp. 1, 2, 3, and 4 (18 to 100 kg pigs) suggest that the SID Lys requirement to optimize IOFC is considerably lower than the biological requirement for maximal growth performance. However, in Exp. 5 the SID Lys requirement for maximum IOFC and growth performance were more closely aligned (0.59 to 0.64%). These results would suggest that, in the economic scenarios considered in our analysis, there is no economic advantage to feed pigs to their maximum biological growth performance when they weigh less than 100 kg. However, in late-finishing pigs (103 to 128 kg) maximum economic performance is achieved at similar levels as maximum growth performance.

In conclusion, the SID Lys estimate for maximum IOFC and growth performance was determined for 5 different weight ranges from 18 to 128 kg. In addition, prediction equations were developed to describe the Lys:calorie ratio that best met biological requirements for growth performance and optimized IOFC. Therefore, this data can be used to formulate SID Lys diet levels for Duroc-sired pigs ranging in weight from 18 to 128 kg.

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Table 1.1 Diet composition (Exp. 1; as-fed basis)[1]

	SID Lys, %					
Item	1.00	1.10	1.20	1.30	1.40	1.50
Ingredient, %						
Corn	69.40	66.55	63.67	60.81	57.93	55.13
Soybean meal, 46.5% CP	25.61	28.11	30.61	33.11	35.61	38.11
Corn oil	2.00	2.25	2.50	2.75	3.00	3.20
Limestone	1.00	1.00	0.98	0.98	0.95	0.95
Monocalcium P, 21% P	0.70	0.65	0.65	0.60	0.60	0.55
Sodium chloride	0.50	0.50	0.50	0.50	0.50	0.50
L-Lys-HCl	0.25	0.30	0.35	0.40	0.45	0.50
DL-Met	0.07	0.11	0.15	0.19	0.23	0.26
L-Thr	0.08	0.11	0.14	0.17	0.20	0.23
L-Trp	0.01	0.01	0.02	0.02	0.03	0.03
L-Val	0.00	0.02	0.05	0.08	0.11	0.15
Vitamin premix with phytase[2]	0.25	0.25	0.25	0.25	0.25	0.25
Trace mineral premix[3]	0.15	0.15	0.15	0.15	0.15	0.15
Total	100	100	100	100	100	100
Calculated analysis[4]						
SID AA, %						
Lys, %	1.00	1.10	1.20	1.30	1.40	1.50
Ile:Lys	65	63	61	59	58	57
Leu:Lys	140	132	126	120	116	112
Met:Lys	32	34	35	36	37	37
Met and Cys:Lys	58	58	58	58	58	58
Thr:Lys	63	63	63	63	63	63
Trp:Lys	19.2	19.1	19.1	19.1	19.0	19.0
Val:Lys	71	70	70	70	70	70
His:Lys	43	41	40	39	38	37
Total Lys, %	1.13	1.23	1.34	1.45	1.55	1.65
NE, kcal/kg	2,553	2,553	2,553	2,553	2,553	2,553
SID Lys:NE, g/Mcal	3.92	4.31	4.70	5.09	5.48	5.88
CP, %	18.3	19.3	20.4	21.5	22.6	23.7
Ca, %	0.68	0.68	0.68	0.68	0.68	0.68
STTD P, %	0.40	0.40	0.40	0.40	0.40	0.40

[1]Diets were fed from 18.4 to 40.2 kg BW.

[2]Ronozyme Hiphos (GT) 2700 (DSM Nutritional Products, Inc, Parsippany NJ), provided 1248 phytase units (FYT/kg), for an estimated release of 0.12% STTD P. Provided per kilogram of premix: 1,653,465 IU Vitamin A, 661,386 IU Vitamin D_3, 17,637 IU Vitamin E, 1323 mg Vitamin K, 13 mg Vitamin B_{12}, 19,842 mg niacin, 11,023 mg pantothenic acid, 3,306 mg menadione.

[3]Provided per kilogram of premix: 11 g Cu, 0.2 g I, 73 g Fe, 22 g Mn, 0.2 g of Se, 73 g Zn.
[4]Ingrdient values and SID coefficients were derived from NRC. 2012. Nutrient Requirements of Swine, 11th ed. Natl. Acad. Press, Washington D.C.

Table 1.2 Diet composition (Exp. 2 and 3; as-fed basis)

	Exp. 2		Exp. 3	
	SID Lys, %[1]		SID Lys, %[2]	
Item	0.80	1.20	0.65	1.00
Ingredient, %				
Corn	78.62	64.75	83.12	71.87
Soybean meal, 46.5% CP	16.62	31.13	13.15	24.69
Corn oil	1.65	1.00	1.40	1.00
Limestone	1.00	0.98	0.80	0.78
Monocalcium P, 21% P	0.90	0.70	0.58	0.43
Sodium chloride	0.50	0.50	0.50	0.50
L-Lys-HCl	0.28	0.33	0.19	0.28
DL-Met	0.03	0.13	0.02	0.10
L-Thr	0.08	0.12	0.04	0.11
L-Trp	0.02	0.01	0.01	0.01
L-Val	0.01	0.06	0.01	0.05
Vitamin premix with phytase[3]	0.15	0.15	0.10	0.10
Trace mineral premix[4]	0.15	0.15	0.10	0.10
Total	100	100	100	100
Calculated analysis[5]				
SID AA, %				
Lys, %	0.80	1.20	0.65	1.00
Ile:Lys	62	62	68	64
Leu:Lys	148	128	171	139
Met:Lys	31	34	33	35
Met and Cys:Lys	58	58	65	61
Thr:Lys	63	63	66	65
Trp:Lys	19	19	19	19
Val:Lys	72	72	80	75
His:Lys	44	41	49	43
Total Lys, %	0.91	1.34	0.75	1.13
NE, kcal/kg	2,698	2,698	2,698	2,703
SID Lys:NE, g/Mcal	2.96	4.45	2.41	3.70
CP, %	14.8	20.7	13.4	18.1
Ca, %	0.67	0.67	0.51	0.51
STTD P, %	0.40	0.40	0.32	0.32

[1]Diets were fed from 36.3 to 54.2 kg BW. The two diets were blended to create intermediate treatment diets containing 0.88, 0.96, 1.04, and 1.12% SID Lys, respectively.

[2]Diets were fed from 53.2 to 74.2 kg BW. The two diets were blended to create intermediate treatment diets containing 0.72, 0.79, 0.86, and 0.93% SID Lys, respectively.

[3]Ronozyme Hiphos (GT) 2700 (DSM Nutritional Products, Inc, Parsippany NJ), provided 748 or 500 phytase units (FYT/kg), for an estimated release of 0.10 or 0.09% STTD P, in Exp. 2 and 3, respectively. Provided per kilogram of premix: 1,653,465 IU Vitamin A, 661,386 IU Vitamin D_3, 17,637 IU Vitamin E, 1323 mg Vitamin K, 13 mg Vitamin B_{12}, 19,842 mg niacin, 11,023 mg pantothenic acid, 3,306 mg menadione.

[4]Provided per kilogram of premix: 11 g Cu, 0.2 g I, 73 g Fe, 22 g Mn, 0.2 g of Se, 73 g Zn.

[5]Ingrdient values and SID coefficients were derived from NRC. 2012. Nutrient Requirements of Swine, 11th ed. Natl. Acad. Press, Washington D.C.

Table 1.3 Diet composition (Exp. 4 and 5; as-fed basis)

	Exp. 4		Exp. 5	
	SID Lys, %[1]		SID Lys, %[2]	
Item	0.58	1.00	0.43	0.78
Ingredient, %				
Corn	85.26	71.87	87.36	81.71
Soybean meal, 46.5% CP	10.94	24.69	10.19	14.90
Corn oil	1.50	1.00	0.40	0.90
Limestone	0.80	0.78	0.80	0.80
Monocalcium P, 21% P	0.60	0.43	0.55	0.50
Sodium chloride	0.50	0.50	0.50	0.50
L-Lys-HCl	0.17	0.28	---	0.30
DL-Met	---	0.10	---	0.05
L-Thr	0.03	0.11	---	0.11
L-Trp	---	0.01	---	0.02
L-Val	---	0.05	---	0.02
Vitamin premix with phytase[3]	0.10	0.10	0.10	0.10
Trace mineral premix[4]	0.10	0.10	0.10	0.10
Total	100	100	100	100
Calculated analysis[5]				
SID AA, %				
Lys, %	0.58	1.00	0.43	0.78
Ile:Lys	70	64	92	60
Leu:Lys	183	139	245	148
Met:Lys	33	35	44	33
Met and Cys:Lys	67	61	89	60
Thr:Lys	66	65	81	66
Trp:Lys	18	19	24	19
Val:Lys	82	75	109	72
His:Lys	51	43	68	43
Total Lys, %	0.67	1.13	0.52	0.88
NE, kcal/kg	2,698	2,703	2,577	2,579
SID Lys:NE, g/Mcal	2.15	3.70	1.57	3.02
CP, %	12.4	18.1	12.1	14.3
Ca, %	0.51	0.51	0.50	0.50
STTD P, %	0.32	0.32	0.31	0.31

[1]Diets were fed from 76.4 to 99.1 kg BW. The two diets were blended to create intermediate treatment diets containing 0.65, 0.72, 0.79, 0.86, and 0.93% SID Lys, respectively.

[2]Diets were fed from 103.8 to 127.3 kg BW. The two diets were blended to create intermediate treatment diets containing 0.50, 0.57, 0.64, and 0.71% SID Lys, respectively.

[3]Ronozyme Hiphos (GT) 2700 (DSM Nutritional Products, Inc, Parsippany NJ), provided 500 phytase units (FYT/kg), for an estimated release of 0.09% STTD P. Provided per kilogram of premix: 1,653,465 IU Vitamin A, 661,386 IU Vitamin D_3, 17,637 IU Vitamin E, 1323 mg Vitamin K, 13 mg Vitamin B_{12}, 19,842 mg niacin, 11,023 mg pantothenic acid, 3,306 mg menadione.

[4]Provided per kilogram of premix: 11 g Cu, 0.2 g I, 73 g Fe, 22 g Mn, 0.2 g of Se, 73 g Zn.

[5]Ingrdient values and SID coefficients were derived from NRC. 2012. Nutrient Requirements of Swine, 11th ed. Natl. Acad. Press, Washington D.C.

Table 1.4 Amino acid analysis of diets (Exp. 1; as-fed basis)[1]

	SID Lys, %					
Item	1.00	1.10	1.20	1.30	1.40	1.50
Amino acid analysis, %[2]						
Lys	1.16	1.30	1.34	1.48	1.52	1.64
Ile	0.74	0.81	0.76	0.87	0.90	0.95
Met	0.35	0.40	0.38	0.45	0.50	0.53
Met + Cys	0.64	0.71	0.70	0.80	0.83	0.89
Thr	0.79	0.88	0.90	1.02	1.05	1.11
Trp	0.24	0.25	0.28	0.31	0.31	0.33
Val	0.83	0.91	0.88	1.00	1.07	1.14
His	0.48	0.51	0.50	0.55	0.55	0.59
Phe	0.98	1.04	1.02	1.12	1.13	1.17

[1]Diet samples were taken from every 3rd bag of feed 7 d after the beginning of the trial and stored at -20°C. Values are reported on a total analyzed basis.

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

Table 1.5 Amino acid analysis of diets (Exp. 2, 3, 4, and 5; as-fed basis)[1]

	Exp. 2		Exp. 3		Exp. 4		Exp. 5	
	SID Lys, %		SID Lys, %		SID Lys, %		SID Lys, %	
Item	0.80	1.20	0.65	1.00	0.58	1.00	0.43	0.79
Amino acid analysis, %[2]								
Lys	0.95	1.26	0.83	1.19	0.78	1.18	0.55	1.15
Ile	0.58	0.80	0.52	0.74	0.49	0.75	0.48	0.75
Met	0.25	0.41	0.22	0.35	0.19	0.33	0.23	0.34
Met + Cys	0.43	0.69	0.45	0.64	0.39	0.61	0.44	0.63
Thr	0.59	0.76	0.49	0.72	0.44	0.65	0.46	0.73
Trp	0.17	0.25	0.15	0.22	0.12	0.22	0.14	0.24
Val	0.69	0.93	0.64	0.87	0.59	0.87	0.61	0.86
His	0.43	0.56	0.40	0.53	0.39	0.53	0.31	0.47
Phe	0.81	1.05	0.74	0.98	0.68	1.01	0.62	0.94

[1]Diet samples were taken from 6 feeders 3 d after the beginning of the trial and stored at -20°C. Values are reported on a total analyzed basis.

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

Table 1.6 Effects of increasing SID Lys on growth performance of pigs weighing 18 to 40 kg (Exp. 1)[1]

	SID Lys, %							*P* =	
Item	1.00	1.10	1.20	1.30	1.40	1.50	SEM	Linear	Quadratic
BW, kg									
d 0	18.4	18.5	18.4	18.4	18.4	18.4	0.50	0.918	0.863
d 24	39.0	39.9	39.9	39.6	40.1	40.2	0.86	0.040	0.537
Overall (d 0 to 24)									
ADG, g	844	889	895	888	894	907	17.0	0.003	0.166
ADFI, g	1,477	1,468	1,472	1,429	1,445	1,411	31.2	0.012	0.676
G:F, g/kg	572	605	609	622	620	643	6.4	< 0.001	0.212
SID Lys g/d	14.74	16.12	17.63	18.53	20.19	21.12	0.386	< 0.001	0.470
SID Lys g/kg gain	17.46	18.15	19.69	20.87	22.59	23.28	0.218	< 0.001	0.719
Economics, $									
High ingredient and pig prices[2]									
Feed cost/pig	11.91	12.49	12.73	12.92	13.47	13.64	0.314	< 0.001	0.702
Feed cost/kg gain[3]	0.583	0.573	0.592	0.602	0.628	0.625	0.0064	< 0.001	0.272
Total revenue/pig[4]	29.82	31.85	31.37	31.33	31.32	31.83	0.689	0.074	0.265
IOFC[5]	17.91	19.36	18.64	18.41	17.85	18.20	0.429	0.304	0.169
Low ingredient and pig prices[6]									
Feed cost/pig	7.54	7.99	8.22	8.42	8.85	9.03	0.203	< 0.001	0.673
Feed cost/lb gain	0.369	0.366	0.383	0.392	0.413	0.414	0.0019	< 0.001	0.339
Total revenue/pig[4]	20.22	21.60	21.27	21.24	21.24	21.59	0.467	0.074	0.265
IOFC	12.68	13.61	13.05	12.82	12.38	12.56	0.300	0.048	0.181

[1]A total of 300 pigs (DNA 600 × 241; initially 18.4 ± 0.50 kg BW) were used with 5 pigs per pen and 10 replications per treatment.
[2] For high priced diets, corn was valued at $6.00/bu ($235.71/tonne), soybean meal at $440/tonne, L-Lys at $1.76/kg, DL-Met at $5.51/kg, L-Thr at $2.65/kg, L-Trp at $11.02/kg, and L-Val at $8.82/kg.
[3] Feed cost/lb gain = (feed cost/pig) / total gain.
[4] Total revenue/pig = total gain/pig × gain value ($1.46/kg at high prices; $0.99/kg at low prices)
[5] Income over feed cost = total revenue/pig – feed cost/pig.
[6] For low priced diets, corn was valued at $3.00/bu ($117.86/tonne), soybean meal at $330/tonne, L-Lys at $1.43/kg, DL-Met at $3.75/kg, L-Thr at $1.87/kg, L-Trp at $6.61/kg, and L-Val at $5.51/kg.

Table 1.7 Effects of increasing SID Lys on growth performance of pigs weighing 36 to 54 kg (Exp. 2)[1]

	SID Lys, %							*P* =	
Item	0.80	0.88	0.96	1.04	1.12	1.20	SEM	Linear	Quadratic
BW, kg									
Initial	36.3	36.4	36.3	36.4	36.4	36.2	0.91	0.826	0.634
Final	53.9	54.0	54.2	54.3	54.2	54.4	0.93	0.316	0.806
ADG, kg	0.99	0.99	1.01	1.02	1.01	1.03	0.019	0.036	0.952
ADFI, kg	2.03	1.96	1.98	2.01	1.95	1.98	0.032	0.308	0.399
G:F	0.490	0.507	0.512	0.508	0.521	0.522	0.0108	< 0.001	0.374
SID Lys g/d	16.20	17.24	18.98	20.89	21.83	23.82	0.336	< 0.001	0.505
SID Lys g/kg gain	16.24	17.17	18.58	20.75	21.69	22.94	0.624	< 0.001	0.963
Economics, $									
High ingredient and pig prices[2]									
Feed cost/pig	11.03	10.92	11.27	11.56	11.67	11.99	0.646	< 0.001	0.357
Feed cost/kg gain[3]	0.639	0.629	0.641	0.655	0.654	0.666	0.0141	0.002	0.424
Total revenue/pig[4]	25.61	25.75	26.13	26.114	26.24	26.56	1.865	0.060	0.949
IOFC[5]	14.58	14.83	14.86	14.58	14.57	14.57	1.235	0.669	0.624
Low ingredient and pig prices[6]									
Feed cost/pig	6.73	6.75	7.01	7.32	7.42	7.71	0.406	< 0.001	0.373
Feed cost/kg gain	0.390	0.389	0.398	0.415	0.416	0.429	0.0088	< 0.001	0.464
Total revenue/pig[4]	17.37	17.46	17.72	17.73	17.79	18.01	1.264	0.060	0.949
IOFC	10.64	10.71	10.71	10.41	10.37	10.29	0.876	0.097	0.659

[1]A total of 608 pigs (600 × 241, DNA; initially 36.3 ± 0.91 kg BW) were used in 2 groups with 7 to 9 pigs per pen and 12 replications per treatment. A total of 285 pigs (initially 38.9 ± 0.81 kg BW) were fed trial diets for a 14-day period for group 1, and 323 pigs (initially 34.1 ± 0.95 kg BW) were fed trial diets for a 21-day period for group 2.

[2] For high priced diets, corn was valued at $6.00/bu ($235.71/tonne), soybean meal at $440/tonne, L-Lys at $1.76/kg, DL-Met at $5.51/kg, L-Thr at $2.65/kg, L-Trp at $11.02/kg, and L-Val at $8.82/kg.

[3] Feed cost/lb gain = (feed cost/pig) / total gain.

[4] Total revenue/pig = total gain/pig × gain value ($1.46/kg at high prices; $0.99/kg at low prices)

[5] Income over feed cost = total revenue/pig – feed cost/pig.

[6] For low priced diets, corn was valued at $3.00/bu ($117.86/tonne), soybean meal at $330/tonne, L-Lys at $1.43/kg, DL-Met at $3.75/kg, L-Thr at $1.87/kg, L-Trp at $6.61/kg, and L-Val at $5.51/kg.

Table 1.8 Effects of increasing SID Lys lysine on growth performance of pigs weighing 53 to 75 kg (Exp. 3)[1]

	SID Lys, %							*P* =	
Item	0.65	0.72	0.79	0.86	0.92	1.00	SEM	Linear	Quadratic
BW, kg									
d 0	53.1	53.2	53.2	53.2	53.1	53.2	0.86	0.926	0.857
d 21	72.9	73.4	74.1	74.2	74.7	75.7	1.03	< 0.001	0.804
Overall (d 0 to 21)									
ADG, kg	0.94	0.96	1.00	1.01	1.03	1.06	0.017	< 0.001	0.910
ADFI, kg	2.42	2.33	2.33	2.32	2.32	2.38	0.048	0.295	0.004
G:F	0.389	0.413	0.429	0.434	0.444	0.447	0.0050	< 0.001	0.001
SID Lys g/d	15.79	16.78	18.37	19.97	21.56	23.94	0.396	< 0.001	0.003
SID Lys g/kg gain	16.76	17.47	18.43	19.83	20.96	22.58	0.220	< 0.001	0.002
Economics, $									
High ingredient and pig prices[2]									
Feed cost/pig	15.04	15.23	15.07	15.53	15.57	16.45	0.344	< 0.001	0.023
Feed cost/kg gain[3]	0.760	0.733	0.720	0.727	0.721	0.738	0.0084	0.012	< 0.001
Total revenue/pig[4]	28.89	30.31	30.54	31.20	31.53	32.59	0.568	< 0.001	0.745
IOFC[5]	13.85	15.07	15.47	15.68	15.96	16.14	0.327	< 0.001	0.064
Low ingredient and pig prices[6]									
Feed cost/pig	8.64	8.78	8.83	9.23	9.34	10.05	0.203	< 0.001	0.006
Feed cost/kg gain	0.437	0.422	0.422	0.432	0.432	0.451	0.0050	0.002	< 0.001
Total revenue/pig	19.59	20.55	20.71	21.16	21.38	22.10	0.385	< 0.001	0.745
IOFC	10.95	11.77	11.88	11.93	12.04	12.05	0.237	0.002	0.062

[1]A total of 700 pigs (DNA 600 × 241; initial BW of 53.2 ± 0.86 kg) were used with 8 to 10 pigs per pen and 12 replications per treatment and were fed trial diets for a 21-d period in two groups.
[2] For high priced diets, corn was valued at $6.00/bu ($235.71/tonne), soybean meal at $440/tonne, L-Lys at $1.76/kg, DL-Met at $5.51/kg, L-Thr at $2.65/kg, L-Trp at $11.02/kg, and L-Val at $8.82/kg.
[3] Feed cost/lb gain = (feed cost/pig) / total gain.
[4] Total revenue/pig = total gain/pig × gain value ($1.46/kg at high prices; $0.99/kg at low prices)
[5] Income over feed cost = total revenue/pig – feed cost/pig.
[6] For low priced diets, corn was valued at $3.00/bu ($117.86/tonne), soybean meal at $330/tonne, L-Lys at $1.43/kg, DL-Met at $3.75/kg, L-Thr at $1.87/kg, L-Trp at $6.61/kg, and L-Val at $5.51/kg.

Table 1.9 Effects of increasing SID Lys lysine on growth performance of pigs weighing 76 to 100 kg (Exp. 4)[1]

	SID Lys, %								*P* =	
Item	0.58	0.65	0.72	0.79	0.86	0.92	1.00	SEM	Linear	Quadratic
BW, kg										
d 0	76.5	76.5	76.2	76.5	76.4	76.2	76.2	1.24	0.499	0.936
d 21	98.4	99.0	98.7	99.3	99.4	99.3	99.3	1.37	0.290	0.538
Overall (d 0 to 21)										
ADG, kg	1.04	1.06	1.07	1.09	1.09	1.10	1.10	0.026	0.022	0.488
ADFI, kg	2.94	2.92	2.89	2.88	2.86	2.89	2.88	0.067	0.357	0.423
G:F	0.355	0.365	0.371	0.378	0.383	0.380	0.382	0.0084	< 0.001	0.097
SID Lys g/d	16.92	18.96	20.79	22.78	24.50	26.91	28.65	0.527	< 0.001	0.874
SID Lys g/kg gain	16.30	17.82	19.43	20.96	22.52	24.54	26.15	0.472	< 0.001	0.398
Economics, $										
High ingredient and pig prices[2]										
Feed cost/pig	17.91	18.29	18.53	18.69	18.94	19.42	19.91	0.470	< 0.001	0.527
Feed cost/kg gain[3]	0.824	0.810	0.815	0.819	0.826	0.844	0.864	0.0178	0.008	0.038
Total revenue/pig[4]	31.79	32.98	33.29	33.28	33.51	33.65	33.84	0.836	0.051	0.405
IOFC[5]	13.64	14.69	14.69	14.66	14.58	14.23	14.21	0.676	0.822	0.151
Low ingredient and pig prices[6]										
Feed cost/pig	10.03	10.51	10.68	10.95	11.26	11.66	12.15	0.274	< 0.001	0.486
Feed cost/kg gain	0.461	0.465	0.470	0.480	0.491	0.506	0.527	0.0105	< 0.001	0.041
Total revenue/pig	21.55	22.36	22.57	22.57	22.73	22.82	22.95	0.567	0.051	0.405
IOFC	11.34	11.85	11.84	11.66	11.47	11.16	11.03	0.464	0.209	0.172

[1]A total of 616 pigs (600 × 241, DNA; initially 76.4 ± 1.24 kg BW) were used in 2 groups with 8 to 10 pigs per pen and 6 replications for the 0.58% SID Lys treatment; 11 replications for the 0.65, 0.72, 0.79, 0.86, and 0.92% SID Lys treatments; and 5 replications for the 1.00% SID Lys treatment.
[2] For high priced diets, corn was valued at $6.00/bu ($235.71/tonne), soybean meal at $440/tonne, L-Lys at $1.76/kg, DL-Met at $5.51/kg, L-Thr at $2.65/kg, L-Trp at $11.02/kg, and L-Val at $8.82/kg.
[3] Feed cost/lb gain = (feed cost/pig) / total gain.
[4] Total revenue/pig = total gain/pig × gain value ($1.46/kg at high prices; $0.99/kg at low prices)
[5] Income over feed cost = total revenue/pig – feed cost/pig.
[6] For low priced diets, corn was valued at $3.00/bu ($117.86/tonne), soybean meal at $330/tonne, L-Lys at $1.43/kg, DL-Met at $3.75/kg, L-Thr at $1.87/kg, L-Trp at $6.61/kg, and L-Val at $5.51/kg.

Table 1.10 Effects of increasing SID Lys on growth performance of pigs weighing 103 to 128 kg (Exp. 5)[1]

	SID Lys, %							*P* =	
Item	0.43	0.50	0.57	0.64	0.71	0.78	SEM	Linear	Quadratic
BW, kg									
Initial	103.8	103.8	103.9	103.6	103.8	103.8	1.32	0.980	0.966
Final	125.9	127.3	127.0	127.6	128.4	127.3	1.14	0.025	0.102
ADG, kg	0.90	0.95	0.94	0.98	1.00	0.95	0.0256	0.043	0.108
ADFI, kg	3.01	3.01	2.90	2.96	2.98	2.89	0.049	0.102	0.956
G:F	0.300	0.315	0.325	0.329	0.334	0.331	0.064	< 0.001	0.032
SID Lys, g/d	12.90	15.03	16.52	18.93	21.12	22.60	0.279	< 0.001	0.408
SID Lys, g/kg gain	14.43	15.87	17.54	19.48	21.30	23.75	0.376	< 0.001	0.178
Economics, $									
High ingredient and pig prices[2]									
Feed cost/pig	20.37	20.86	20.37	21.46	21.89	21.90	0.920	0.115	0.915
Feed cost/kg gain[3]	0.927	0.898	0.884	0.894	0.895	0.922	0.0082	0.929	0.032
Total revenue/pig[4]	32.01	33.84	33.56	34.96	35.62	34.54	1.07	0.028	0.229
IOFC[5]	11.63	12.98	13.18	13.52	13.73	12.65	0.450	0.020	0.001
Low ingredient and pig prices[6]									
Feed cost/pig	11.73	12.06	12.07	12.75	13.13	13.17	0.544	0.014	0.957
Feed cost/kg gain	0.534	0.519	0.524	0.531	0.537	0.555	0.0107	0.044	0.077
Total revenue/pig	21.70	22.95	22.75	23.71	24.15	23.42	0.724	0.028	0.229
IOFC	9.97	10.89	10.69	10.98	11.02	10.25	0.324	0.397	0.004

[1] A total of 679 pigs (600 × 241, DNA; initial BW of 228.8 ± 2.9 lb) were used with 8 to 10 pigs per pen and 12 replications per treatment for the 0.43, 0.50, 0.57, 0.71 and 0.78% SID Lys treatments, 11 replications for the 0.64% SID Lys treatment, and were fed trial diets for a 21- or 28-d period in two groups.

[2] For high priced diets, corn was valued at $6.00/bu ($235.71/tonne), soybean meal at $440/tonne, L-Lys at $1.76/kg, DL-Met at $5.51/kg, L-Thr at $2.65/kg, L-Trp at $11.02/kg, and L-Val at $8.82/kg.

[3] Feed cost/lb gain = (feed cost/pig) / total gain.

[4] Total revenue/pig = total gain/pig × gain value ($1.46/kg at high prices; $0.99/kg at low prices)

[5] Income over feed cost = total revenue/pig – feed cost/pig.

[6] For low priced diets, corn was valued at $3.00/bu ($117.86/tonne), soybean meal at $330/tonne, L-Lys at $1.43/kg, DL-Met at $3.75/kg, L-Thr at $1.87/kg, L-Trp at $6.61/kg, and L-Val at $5.51/kg.

Table 1.11 Summary of the Lys:calorie ratio and associated SID Lys percentage and Lys intake that provided maximal response for growth performance and income over feed cost (IOFC)[1]

Trial	BW range, kg	Midpoint BW, kg	Lys:calorie ratio, g of SID Lys/Mcal of NE	SID Lys, %	SID Lys intake, g/d	SID Lys g/kg of gain
Growth Performance						
Trial 1	18 to 40	29	5.53	1.41	20.37	22.63
Trial 2	36 to 54	46	4.45	1.20	23.80	22.90
Trial 3	53 to 75	64	3.70	0.99	23.56	22.55
Trial 4	76 to 100	88	3.26	0.88	25.30	23.11
Trial 5	103 to 128	116	2.48	0.64	18.93	19.48
IOFC[2]						
Trial 1	18 to 40	29	4.39	1.12	16.46	18.46
Trial 2	36 to 54	46	3.56	0.96	19.00	18.60
Trial 3	53 to 75	64	3.37	0.91	21.11	20.20
Trial 4	76 to 100	88	2.89	0.78	22.50	20.84
Trial 5	103 to 128	116	2.48	0.64	18.93	19.48

[1]Five trials were conducted to determine maximum SID Lys, % in grow-finish pigs (600 × 241, DNA).
[2]Income over feed cost = total revenue/pig – feed cost/pig.

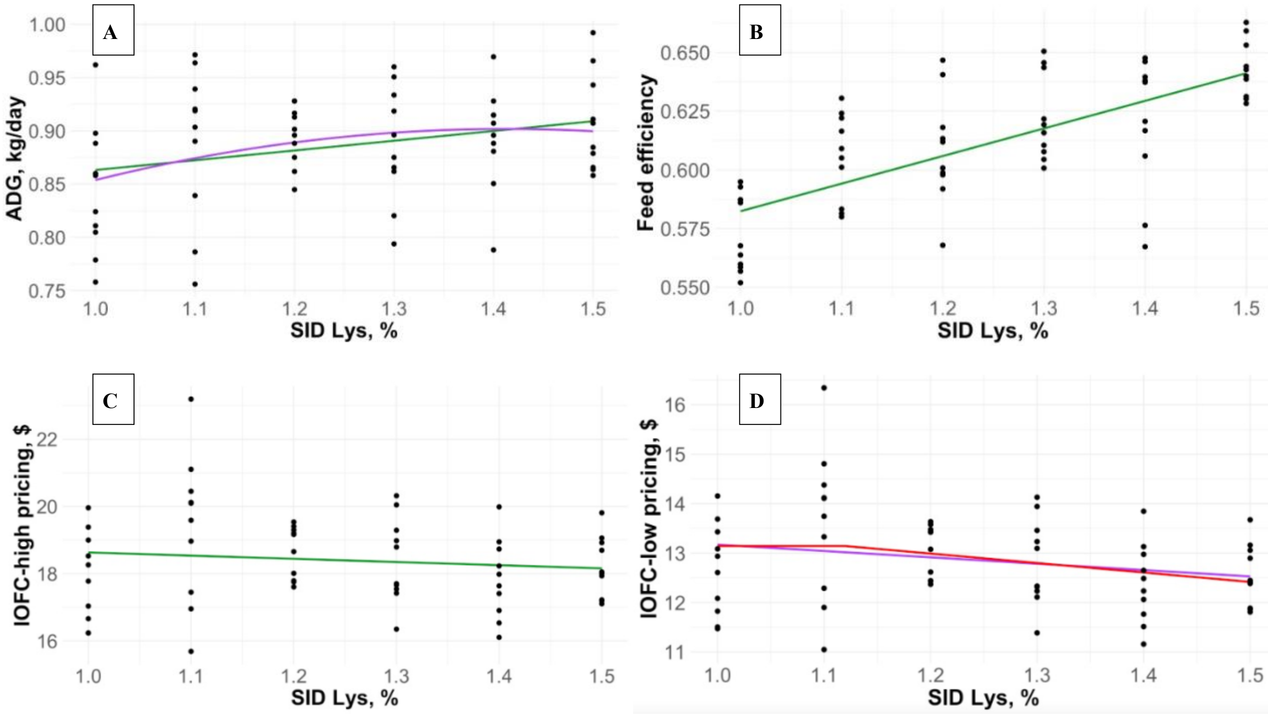

Figure 1.1. Estimation of standardized ileal digestible (SID) lysine requirement to maximize ADG, G:F, and income over feed cost (IOFC) for 18 to 40 kg Duroc-sired pigs (600 × 241, DNA; Exp. 1). A total of 300 pigs (600 × 241, DNA; initially 18.4 ± 0.50 kg) were used in a 24-d growth trial with 5 pigs per pen and 10 replications per treatment. A. The linear model (LM) and quadratic polynomial (QP) models had a comparable fit (BIC = -184.9 and -182.9, LM and QP, respectively) with the SID Lys requirement to achieve maximal ADG predicted above 1.50% with LM and 1.41% with the QP model. The QP model equation was: ADG = -0.282148 × (SID Lys, %)^2 + 0.797053 × (SID Lys, %) + 0.339. B. The LM had the best fit with the SID Lys requirement to achieve maximal feed efficiency predicted above 1.50% C. The LM was the best fitting model with the SID Lys requirement to achieve maximal IOFC with high ingredient and pig prices predicted at less than 1.00% SID Lys. D. The LM and BLL models had a comparable fit (BIC = 178.0 and 179.4, LM and BLL, respectively) with the SID Lys requirement to achieve maximal IOFC with low ingredient and pig prices predicted at less than 1.00% with the LM, and 1.12% with the BLL model. The BLL model predicted a reduction in IOFC when SID Lys increased past 1.12% SID Lys.

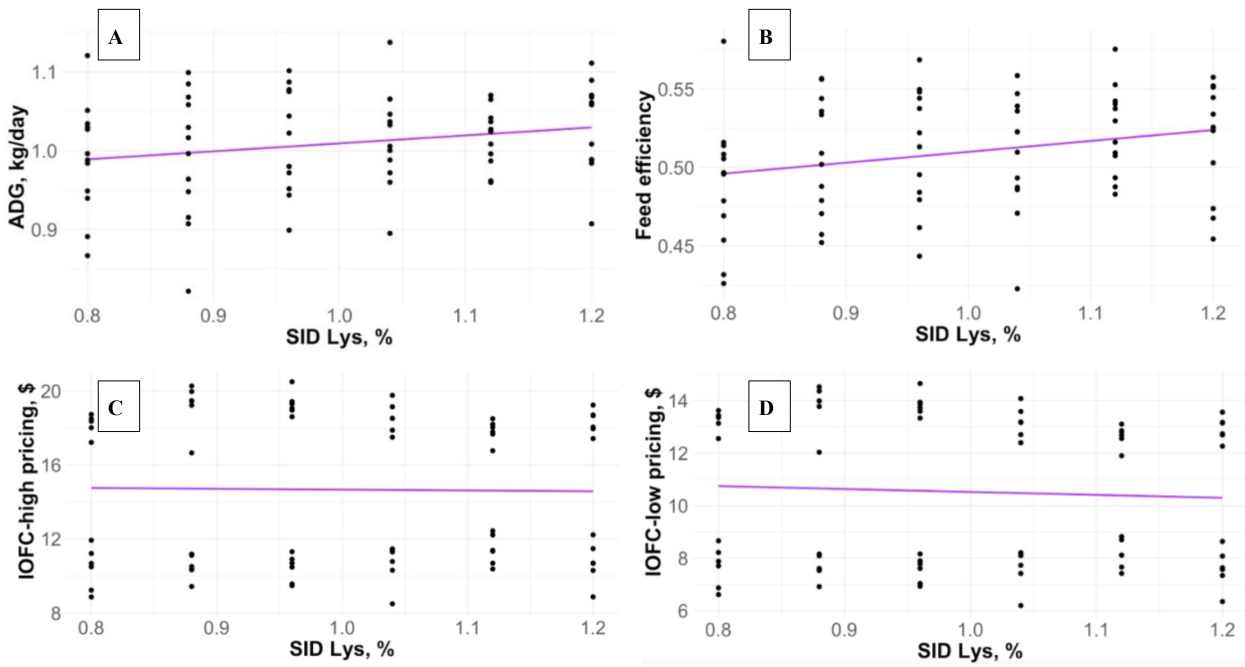

Figure 1.2. Estimation of standardized ileal digestible (SID) lysine requirement to maximize ADG, G:F, and income over feed cost (IOFC) for 36 to 54 kg Duroc-sired pigs (600 × 241, DNA; Exp. 2). A total of 608 pigs (600 × 241, DNA; initially 36.3 ± 0.91 kg BW) were used with in a pair of 14 or 21-d growth trials, with 7 to 9 pigs per pen and 12 replications per treatment. A. The linear model (LM) was the best fitting model with the SID Lys requirement to achieve maximal ADG predicted at greater than 1.20% SID Lys. B. The LM was the best fitting model with the SID Lys requirement to achieve maximal feed efficiency predicted at greater than 1.20% SID Lys. C. The LM was the best fitting model with the SID Lys requirement to achieve maximal IOFC with high ingredient and pig prices predicted at less than 0.80% SID Lys. D. The LM was the best fitting model with the SID Lys requirement to achieve maximal IOFC with low ingredient and pig prices predicted at less than 0.80% SID Lys.

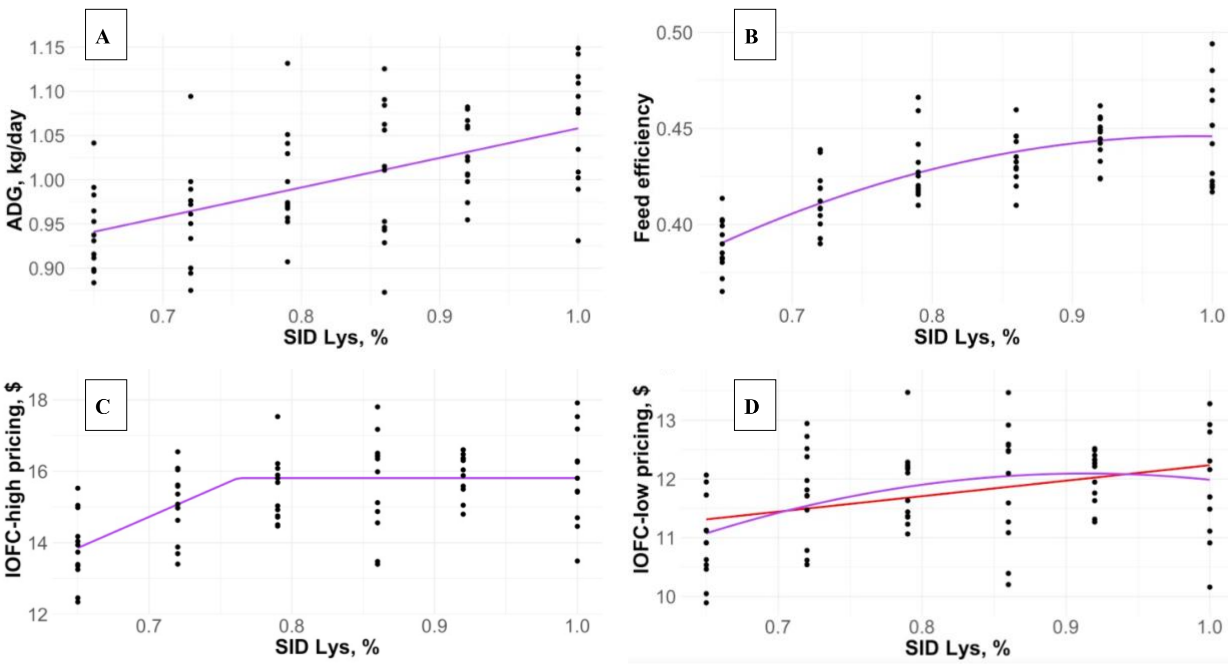

Figure 1.3. Estimation of standardized ileal digestible (SID) lysine requirement to maximize ADG, G:F, and income over feed cost (IOFC) for 53 to 75 kg Duroc-sired pigs (600 × 241, DNA; Exp. 3). A total of 700 pigs (DNA 600 × 241; initial BW of 53.2 ± 0.86 kg) were used in two separate 21-d growth trials, with 8 to 10 pigs per pen and 12 replications per treatment. A. The linear model (LM) was the best fitting model with the SID Lys requirement to achieve maximal ADG predicted above 1.00% SID Lys. B. The quadratic polynomial (QP) was the best fitting model with the SID Lys requirement to achieve maximal feed efficiency predicted at 0.99%. The QP model equation was: G:F = -0.4830938 × (SID Lys, %)^2 + 0.9555893 × (SID Lys, %) – 0.027. C. The broken line linear (BLL) was the best fitting model with the SID Lys requirement to achieve maximal IOFC with high ingredient and pig prices predicted at 0.76%. The BLL predicted no further improvement in IOFC past 0.76% SID Lys. D. The LM and QP models had a comparable fit (BIC = 191.8 and 192.4, LM and QP, respectively) with the SID Lys requirement to achieve maximal IOFC with low ingredient and pig prices predicted above 1.00% with the LM, and 0.91% with the QP. The QP model equation was: IOFC = -14.5626 × (SID Lys, %)^2 + 26.6348 × (SID Lys, %) - 0.085.

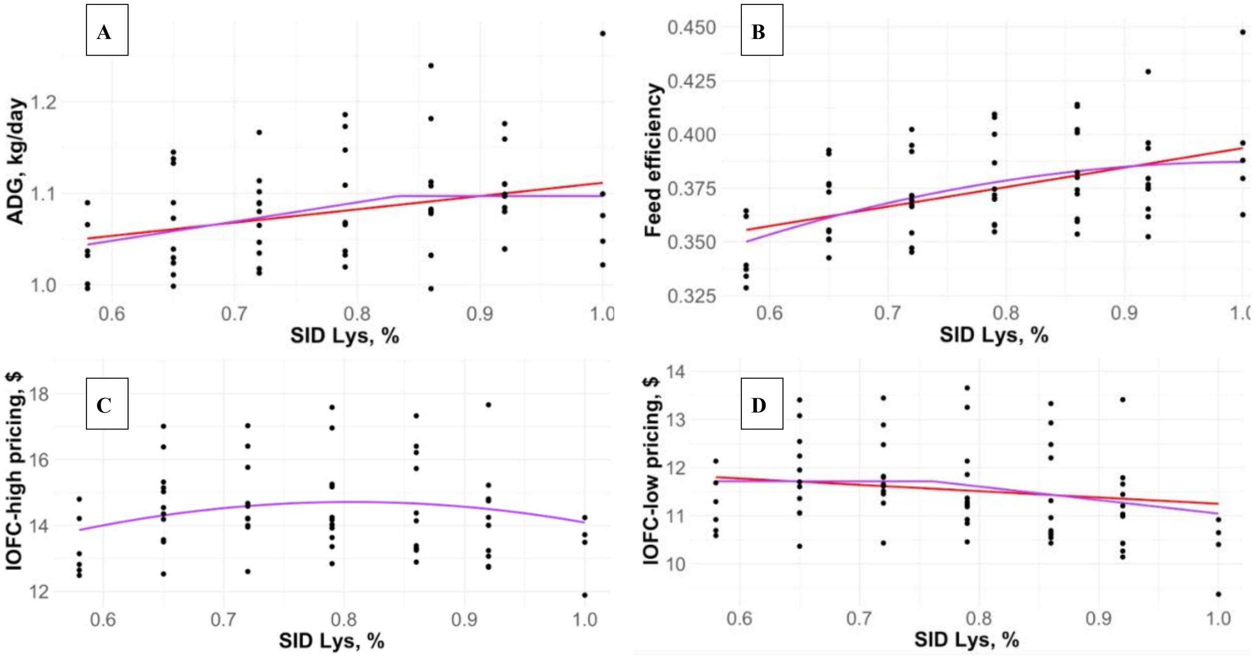

Figure 1.4. Estimation of standardized ileal digestible (SID) lysine requirement to maximize ADG, G:F, and income over feed cost (IOFC) for 76 to 100 kg Duroc-sired pigs (600 × 241, DNA; Exp. 4). A total of 616 pigs (600 × 241, DNA; initially 76.4 ± 1.24 kg BW) were used in two separate 21-d growth trials, with 8 to 10 pigs per pen and 6 replications for the 0.58% SID Lys treatment; 11 replications for the 0.65, 0.72, 0.79, 0.86, and 0.92% SID Lys treatments; and 5 replications for the 1.00% SID Lys treatment. A. The broken line linear (BLL) and linear model (LM) models had a comparable fit (BIC = -179.4 and -179.1, BLL and LM, respectively) with the SID Lys requirement to achieve maximal ADG predicted at 0.83% with the BLL, and greater than 1.00% with the LM model. The BLL predicted no further improvement in ADG past 0.83% SID Lys. B. The LM and quadratic polynomial (QP) models had a comparable fit (BIC = -330.1 and -331.0, LM and QP, respectively) with the SID Lys requirement to achieve maximal feed efficiency predicted at greater than 1.00% with the LM, and 0.93% with the QP model. The QP equation model was: G:F = -0.2244707 × (SID Lys, %)^2 + 0.4156878 × (SID Lys, %) + 0.190. C. The QP was the best fitting model with the SID Lys requirement to achieve maximal IOFC at high ingredient and pig prices predicted at 0.78% SID Lys. The QP model equation was: IOFC = -17.3293 × (SID Lys, %)^2 + 27.0408 × (SID Lys, %) + 4.169. D. The BLL and LM models had a comparable fit (BIC = 202.5 and 202.6, BLL and LM, respectively) with the SID Lys requirement to achieve maximal IOFC at low ingredient ant pig prices predicted at 0.76% with the BLL, and less than 0.58% with the LM model. The BLL model predicted a reduction in IOFC when SID Lys increased past 0.76% SID Lys.

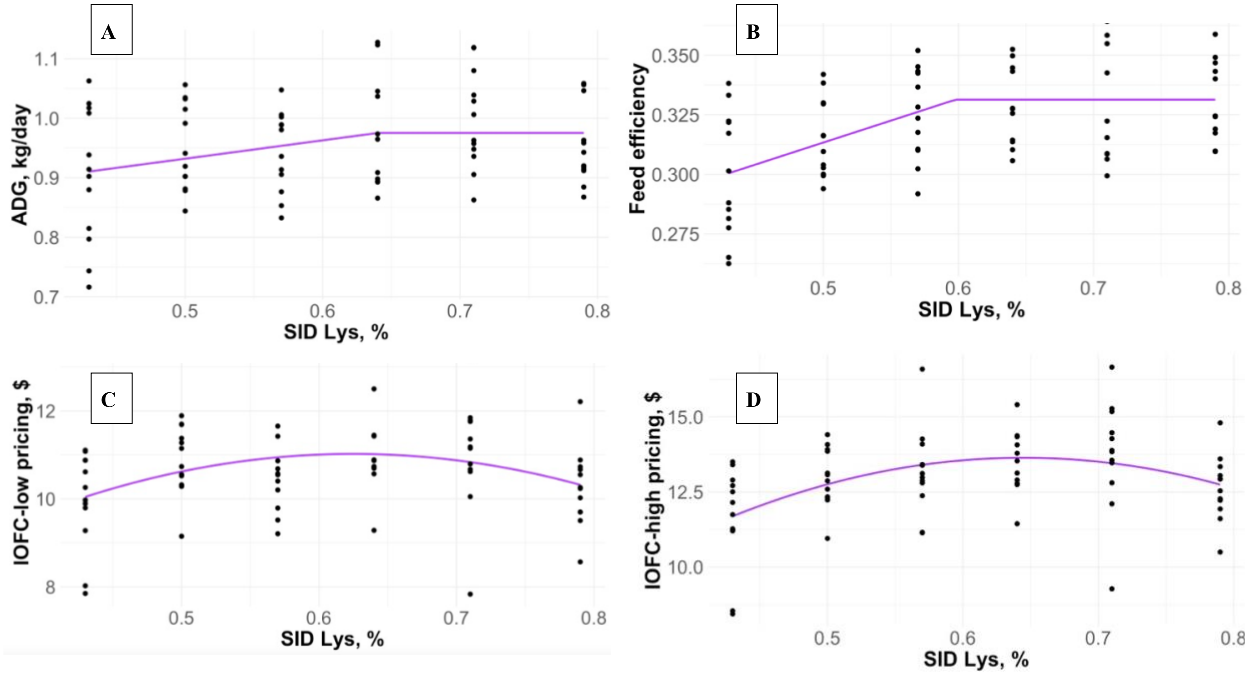

Figure 1.5. Estimation of standardized ileal digestible (SID) lysine requirement to maximize ADG, G:F, and income over feed cost (IOFC) for 103 to 128 kg Duroc-sired pigs (600 × 241, DNA; Exp. 5). A total of 679 pigs (600 × 241, DNA; initial BW of 228.8 ± 2.9 lb) were used in two separate 21- or 28-d growth trials, with 8 to 10 pigs per pen and 12 replications per treatment for the 0.43, 0.50, 0.57, 0.71 and 0.78% SID Lys treatments, 11 replications for the 0.64% SID Lys treatment. A. The broken line linear (BLL) was the best fitting model with the SID Lys requirement to achieve maximal ADG predicted at 0.64%. The BLL predicted no further improvement in ADG past 0.64% SID Lys. B. The BLL was the best fitting model with the SID Lys requirement to achieve maximal feed efficiency predicted at 0.59%. The BLL predicted no further improvement in feed efficiency past 0.59% SID Lys. C. The quadratic polynomial (QP) was the best fitting model with the SID Lys requirement to achieve maximal IOFC at high ingredient and pig prices predicted at 0.64% SID Lys. The QP model equation was: IOFC = -42.60278 × (SID Lys, %)^2 + 54.9097 × (SID Lys, %) – 4.047. D. The QP was the best fitting model with the SID Lys requirement to achieve maximal IOFC at low ingredient and pig prices predicted at 0.62% SID Lys. The QP model equation was: IOFC = -25.9430 × (SID Lys, %)^2 + 32.4160 × (SID Lys, %) + 0.901.

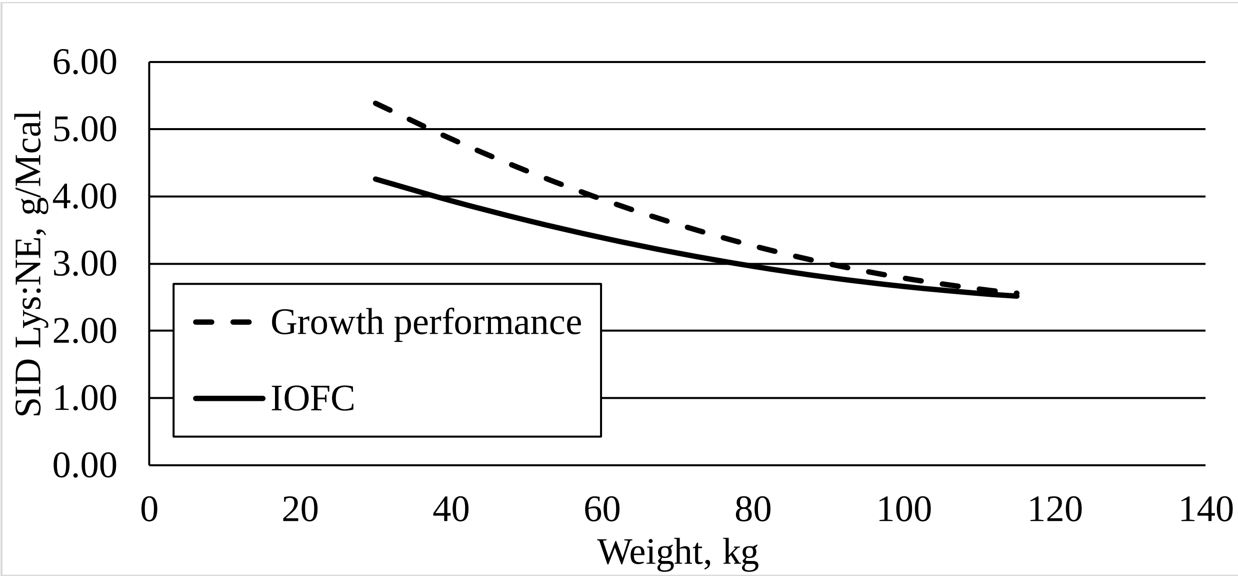

Figure 1.6. Optimal Lys:calorie ratio (g of Lys/Mcal of NE) prediction equations.Optimal Lys:calorie ratio (g of Lys/Mcal of NE) prediction equations were developed for maximum growth performance and IOFC for 18 to 128 kg pigs using our interpretation of 5 trials conducted to determine the maximum SID Lys, % for Duroc-sired pigs (600 × 241, DNA) fed in a university research environment. To maximize growth performance, the quadratic equation is Lys:calorie ratio, g of SID Lys/Mcal of NE = $0.0002611 \times BW^2 - 0.0711037 \times BW + 7.284$. To maximize IOFC, the quadratic equation is Lys:calorie ratio, g of SID Lys/Mcal of NE = $0.0001558 \times BW^2 - 0.04030769 \times BW + 5.410$.

Chapter 2 - Effects of adding potassium bicarbonate to diets with high or low crystalline lysine to influence dietary cation-anion difference on finishing pig growth performance

Abstract

Dietary cation-anion difference (DCAD), calculated as $Na^+ + K^+ – Cl^-$ in mEq/kg of the diet, represents the influence that monovalent cations and anions from these minerals have on the acid-base status of the animal. However, the recommended range of DCAD for optimal grow-finish swine performance is variable, which may indicate an interaction between DCAD and other ingredients. The hypothesis for this study was that the addition of potassium bicarbonate ($KHCO_3$) to increase diet DCAD when high levels of L-Lys HCl (> 0.35% diet) are used may potentially improve growth performance. A total of 1,944 pigs (PIC L337 × 1050, initially 35.2 ± 0.85 kg) were used in a 120-d study. Pens of pigs were blocked by BW and randomly allotted to 1 of 4 dietary treatments in a randomized complete block design. Treatments were arranged in a 2 × 2 factorial with main effects of $KHCO_3$ (0 or 0.4%), and L-Lys HCl level (low or high). There were 27 pigs per pen and 18 replicates per treatment. Treatment diets were corn-soybean meal-based and formulated in four dietary phases (35 to 60 kg, 60 to 85 kg, 85 to 105 kg, and 105 to 130 kg). Dietary treatments were formulated such that in each phase the diet containing a low level of L-Lys HCl without $KHCO_3$ and the diet containing a high level of L-Lys HCl with $KHCO_3$ had similar calculated DCAD values. Additionally, the diet with a low level of L-Lys HCl with $KHCO_3$ was formulated to have the highest DCAD in each phase, while the diet with a high level of L-Lys HCl without $KHCO_3$ was formulated to have the lowest DCAD. Overall, there was no evidence ($P > 0.10$) for a $KHCO_3$ × L-Lys HCl interaction or main effect for final

BW or any observed growth response or carcass characteristics. The results of this study suggest that supplementing $KHCO_3$ to finishing pig diets with either high or low levels of L-Lys HCl and the corresponding changes in DCAD values did not impact growth performance or carcass characteristics.

Key Words: Carcass, crystalline lysine, dietary cation-anion difference, finishing pig, growth, potassium

Introduction

The use of crystalline Lys (L-Lys HCl) to replace a portion of the Lys provided by soybean meal or other intact protein sources to growing-finishing pigs is common in the swine industry. Feeding high levels of dietary Cl^- (via $CaCl_2$) has been shown to greatly decrease growth performance of growing finishing pigs (Yen et al., 1981; Patience et al., 1987; Jones et al., 2019), while a smaller reduction in growth performance has been observed when feeding high levels of L-Lys HCl (Gomez et al., 2002; Lee et al., 2001). This reduction in performance may have been due to a reduction in the dietary cation-anion difference (DCAD, $Na^+ + K^+ - Cl^-$, mEq/kg diet). It is known that feed intake and growth performance of pigs are related to DCAD at extreme levels with the optimum level to maximize performance hypothesized to be anywhere between 75 and 500 mEq/kg of the diet (Patience et al., 1987; Haydon et al., 1990; Dersjant-Li et al., 2001; Jones et al., 2019). Additionally, the replacement of soybean meal with L-Lys HCl in a diet reduces diet DCAD, as the level of dietary K^+ is lowered because soybean meal contains nearly seven times the concentration of K^+ of that in corn (Kephart and Sherritt, 1990; NRC, 2012). This decrease in DCAD may be rectified by the addition of monovalent cations, such as Na^+ or K^+, to balance intracellular anions, thus potentially regaining lost performance.

Numerous studies have been conducted to determine the optimum DCAD level for growth performance, utilizing a variety of monovalent ion sources with varying results. The supplementation of monovalent cations (via $KHCO_3$, KCL, or $NaHCO_3$) has been shown to recover part, or all, of the lost performance resulting from increased Cl^- concentration (Yen et al., 1981; Patience et al., 1987, Dersjant-Li et al., 2001). However, the DCAD level required to optimize growth performance has varied across studies, Therefore, the objective of this experiment was to evaluate the effect of balancing DCAD levels, via added $KHCO_3$, to diets containing low or high levels of L-Lys HCl on growth performance and carcass characteristics of growing-finishing pigs.

Materials and Methods

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. This study was conducted at a commercial research-finishing site in southwest Minnesota (New Horizon Farms, Pipestone, MN). The barns were naturally ventilated and double-curtain sided, with completely slatted concrete flooring over deep pits for manure storage. Each pen (3.05 × 5.49 m) was equipped with a 5-hole stainless steel dry feeder (Thorp Equipment, Inc., Thorp, WI) and 1 cup waterer for *ad libitum* access to feed and water.

A total of 1,944 pigs (PIC L337 × 1050, initially 35.2 ± 0.85, kg) were used in a 120-d study, split between 2 identical barns with 27 pigs per pen and 18 replicates per treatment. Pens of pigs were blocked by initial BW and randomly allotted to 1 of 4 dietary treatments in a randomized complete block design arranged in a 2 × 2 factorial. Main effects were $KHCO_3$ (0 or 0.4%), and L-Lys HCl level (low or high). 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 New Horizon Farms

Feed Mill in Pipestone, MN, and fed in meal form in 4 dietary phases from approximately 35 to 60 kg, 60 to 85 kg, 85 to 105 kg, and 105 to 130 kg (Table 2.1).

Diets were corn-soybean meal-based and formulated with either low or high levels of L-Lys HCl with the addition of other feed-grade amino acids. Dietary cation-anion difference values were calculated using the following equation derived by Mongin (1981): DCAD, mEq/kg = (Na^+ × 434.98) + (K^+ × 255.74) – (Cl^- × 282.06) using NRC (2012) mineral estimates for ingredients. Dietary treatments were formulated such that in each phase the diet containing a low level of L-Lys HCl (0.14 to 0.21% depending on phase) without $KHCO_3$ had a similar calculated DCAD as the diet containing a high level of L-Lys HCl (0.36 to 0.43% depending on phase) with $KHCO_3$. The DCAD for these two treatments were approximately 230, 200, 184, and 169 mEq/kg (phase 1, 2, 3, and 4, respectively). The diets with low levels of L-Lys HCl with $KHCO_3$ had the highest DCAD in each phase (approximately 50 mEq/kg above the low L-Lys HCl without $KHCO_3$ diet), while the diets with a high level of L-Lys HCl without $KHCO_3$ had the lowest DCAD (approximately 50 mEq/kg below the high L-Lys HCl with $KHCO_3$ diet).

Pens of pigs were weighed, and feed disappearance measured approximately every 14 d to determine ADG, ADFI, and G:F. The 3 heaviest pigs from each pen were marketed on approximately d 98 and included in the growth performance data, but not in carcass data. At the completion of the study, final pen weights were taken, individual pigs were tattooed with a pen identification number, and transported to a commercial abattoir (JBS, Worthington, MN) for processing and carcass data collection. Carcass measurements included HCW, backfat depth, loin depth, and percentage lean. Carcass yields were then calculated by the pen average HCW from the plant divided by the pen average final BW on the farm.

Chemical analysis

Diet samples were collected from feeders from each treatment during intermediate weighing events for each dietary phase and were stored at -20°C until chemical analysis. Sub-samples of each diet for each dietary phase were ground with a food processor to create a homogeneous sample and then submitted for analysis of DM (method 935.29; AOAC Int., 2012) and CP (method 990.03; AOAC Int., 2012;Ward Laboratories, Inc. Kearney, NE), as well as Na^+ (method 990.08; AOAC Int., 2012), Cl^- (method 969.10; AOAC Int., 2012), and K^+ (method 968.08; AOAC Int., 2012) analysis (Kansas State University Research and Extension Soil Testing Laboratory, Manhattan, KS; Table 2.2). Analyzed mineral values were used to determine analyzed DCAD values ($Na^+ + K^+ – Cl^-$ in mEq/kg of the diet).

Statistical analysis

Data were analyzed as a randomized complete block design for two-way ANOVA using the lmer function from the lme4 package in R (Version 3.5.2, R Core Team. Vienna, Austria), with pen considered as the experimental unit, and initial BW as a blocking factor. Response criteria were tested for the main effects and potential interactions between $KHCO_3$ and L-Lys HCl as fixed effects. Results were considered significant at $P \leq 0.05$, and a marginally significant at $P \leq 0.10$.

Results

At d 58, there was marginally significant evidence ($P = 0.064$) for a main effect of $KHCO_3$ on BW, with diets containing 0.40% $KHCO_3$ having numerically greater BW (Table 2.3). However, during the grower period (d 0 to 58) there was no evidence ($P > 0.10$) for a $KHCO_3$ × L-Lys HCl interaction or any main effect influence on ADG, ADFI or G:F. Throughout the finishing phase (d 58 to 120) or overall (d 0 to 120), there was no evidence ($P >

0.10) for $KHCO_3$ × L-Lys HCl interactions or main effects for ADG, ADFI or G:F. For carcass characteristics, there was no evidence ($P > 0.10$) for $KHCO_3$ × L-Lys HCl interactions or main effects for any observed response variable measured.

Discussion

Dietary cation-anion difference is calculated as $Na^+ + K^+ - Cl^-$ in mEq/kg of the diet and represents the influence of monovalent cations and anions on the acid-base status of the animal. Guyton (1966) observed that the increase in blood Cl^- reduced the reabsorption of HCO_3^-, which in turn led to acidosis, potentially leading to a reduction in feed intake.

When 15 to 33 kg pigs were fed diets ranging in DCAD from -85 to 341 mEq/kg of the diet, increasing DCAD (via changes in $CaCl_2$ and $NaHCO_3$) quadratically increased ADG and ADFI (Patience et al. 1987). A negative exponential model suggested that there was limited additional improvement to ADG or ADFI above a DCAD level of 0 to 75 mEq/kg of the diet (Patience et al. 1987). Yen et al. (1981) observed that supplementing an alkaline salt ($NaHCO_3$) to 62 to 91 kg pigs helped to partially offset the loss in appetite and performance when pigs were fed a diet that contained 4% $CaCl_2$. It is believed that this recovered performance may have been a result of increasing blood buffering capacity, as shown by increased blood HCO_3^- in pigs fed diets containing both $CaCl_2$ and $NaHCO_3$, which may explain the results found by Patience et al. (1987). Haydon et al. (1990) reported that increasing DCAD from 25 to 400 mEq/kg of diet improved ADG and ADFI of 21 to 105 kg growing-finishing pigs. Using a segmented model approach, Haydon et al. (1990) estimated that there was no further improvement in ADG or ADFI when DCAD exceeded 250 mEq/kg of diet. Similarly, Dersjant-Li et al. (2001) observed that 9 to 34 kg pigs fed diets with a DCAD of 200 or 500 mEq/kg of diet had similar ADG and

ADFI, which were significantly greater when compared to pigs fed diets with a DCAD of -100 mEq/kg.

More recently in nursery pigs, Jones et al. (2019) supplemented increasing levels of $CaCl_2$ to reduce the DCAD level of phase 1 and 2 diets fed post-weaning. In this experiment, it was observed that increasing DCAD from 84 to 243 and 29 to 199 mEq/kg (in phase 1 and 2, respectively) improved both ADG and G:F (Jones et al., 2019). These differences in observed optimum DCAD values may be a result of the different phases of production tested in each study. The results of the current trial indicate that growing finishing pigs (35 to 130 kg) reared in a commercial environment can regulate electrolyte and acid-base balance when DCAD levels range between 100 and 289 mEq/kg of diet and have similar growth performance. These results support the findings of Patience et al. (1987) who observed little to no additional improvement in growth performance at DCAD levels above 0 to 75 mEq/kg.

Potassium is an essential dietary mineral for swine and is a key component of numerous physiological processes such as the maintenance of electrolyte balance, neuromuscular function, and serves as an intracellular monovalent cation to help balance anions as part of the Na-K pump (NRC, 2012). The dietary requirement for K^+ of 25 to 135 kg grower-finishing pigs has been estimated between 0.17 and 0.23% (NRC, 2012). While the requirement has been established, numerous studies have been conducted to analyze the effects of feeding supplemental K^+ on growth performance, digestibility, and blood criteria in pigs at various production stages, with varying results. In a study by Jesse et al. (1988), adding 0.70% potassium chloride (KCl) improved ADG in 20 to 47 kg feeder pigs but in subsequent trials, supplementing either 0.70 or 1.50% KCl did not affect ADG or feed efficiency in 19 to 50 kg pigs (Jesse et al. 1988). Similarly, Brumm and Schricker (1989) observed that supplementing 0.48, 0.96, or 1.44% KCl did not alter ADG, ADFI, or feed efficiency in 20 to 90 kg growing-finishing pigs. While there is some variability in response, collectively these results help support the finding of the current study, in which the addition of 0.40% $KHCO_3$ showed no significant impact on any observed growth response.

While the effects of supplemental K^+ and L-Lys HCl on the growth performance and carcass characteristics of swine have been extensively studied separately, there have been few studies that have analyzed these effects in tandem. The implementation of feeding high levels of L-Lys HCl to replace a large portion of the Lys provided by soybean meal to growing-finishing pigs in modern swine production has been shown to restrict growth performance of grower-finishing pigs (Lee et al., 2001; Gomez et al., 2002). These studies attempted to maintain amino acid ratios to avoid deficiencies which would result in reduced performance when replacing soybean meal with L-Lys HCl. Therefore, the reduction in growth performance may have been a result of unintentional reductions in DCAD values, as replacing soybean meal with L-Lys HCl increased the concentration of Cl^-, while reducing K^+ in the diet (Kephart and Sherritt, 1990). Therefore, it was hypothesized that feeding supplemental K^+ may help capture this lost performance. Wahlstrom and Libal (1982) observed that supplementing 1.0% potassium acetate (CH_3CO_2K) improved ADG in diets with high L-Lys HCl (0.4%), but it had no significant effect in diets without L-Lys HCl (19 to 39 kg pigs). However, these results were contradicted by the work of Kephart and Sherritt (1990) in which they found that supplementing either 1.75% potassium glutamate or 0.95% $KHCO_3$ to diets containing 0.625% L-Lys HCl did not significantly impact ADG or feed efficiency (19 to 35 kg pigs). Similarly, Siyoto and Libal (1981) and Soto et al. (2018) found that supplementing 0.4 or 0.24% KCl, respectively, had no impact on growth responses or any observed carcass characteristics in diets containing high levels of L-Lys HCl (0.4 or 0.33% for 17 to 43 kg pigs or 111 to 134 kg pigs, respectively).

In summary, the results of the current research suggest that supplementing $KHCO_3$ to finishing pig diets with either high or low levels of L-Lys HCl and the corresponding changes in dietary DCAD did not impact growth performance or carcass characteristics.

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

Item	L-Lys HCl:	Phase 1 Low	Phase 1 High	Phase 2 Low	Phase 2 High	Phase 3 Low	Phase 3 High	Phase 4 Low	Phase 4 High
Ingredients, %									
Corn		64.64	71.09	71.33	77.60	74.76	81.47	78.08	84.86
Soybean meal, 46.5% CP		31.67	24.57	25.35	18.42	22.14	14.72	19.08	11.67
Choice white grease		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Calcium carbonate		1.00	0.98	0.90	0.90	0.85	0.85	0.80	0.80
Monocalcium P, 21% P		0.70	0.80	0.50	0.60	0.40	0.50	0.20	0.25
Sodium chloride		0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
L-Lys HCl		0.21	0.43	0.19	0.41	0.15	0.38	0.13	0.36
DL-Met		0.06	0.12	0.02	0.09	0.01	0.08	---	0.07
L-Trp		---	0.04	---	0.04	---	0.04	---	0.04
L-Val		---	0.12	---	0.12	---	0.13	---	0.12
Thr biomas[2]		0.06	0.18	0.03	0.16	0.02	0.16	0.04	0.16
Vitamin trace mineral premix[3]		0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Phytase[4]		0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Potassium bicarbonate[5]		+/-	+/-	+/-	+/-	+/-	+/-	+/-	+/-
Total		100	100	100	100	100	100	100	100
Calculated analysis									
SID AA, %									
Lys		1.12	1.12	0.95	0.95	0.84	0.84	0.75	0.75
Ile:Lys		67	56	68	56	71	56	72	56
Leu:Lys		138	123	148	130	158	137	168	144
Met:Lys		30	33	29	33	30	34	31	35
Met and Cys:Lys		56	56	56	56	59	59	61	61
Thr:Lys		61	61	61	61	63	63	66	66
Trp:Lys		19.8	19.7	19.6	19.7	20.1	20.1	20.3	20.0
Val:Lys		73	73	75	75	79	79	82	81
NE, kcal/kg		2,652	2,654	2,659	2,661	2,661	2,665	2,668	2,700
SID Lys:NE, g/Mcal		4.22	4.22	3.57	3.57	3.15	3.15	2.80	2.80
CP, %		20.7	18.3	18.2	15.8	16.9	14.4	15.7	13.2
Ca, %		0.66	0.64	0.56	0.56	0.52	0.51	0.45	0.44
STTD P, %		0.41	0.41	0.36	0.36	0.33	0.33	0.28	0.28

[1]Phase 1 was fed from approximately 35 to 59 kg, phase 2 was fed from approximately 59 to 84 kg, phase 3 was fed from approximately 84 to 104 kg, and phase 4 was fed from approximately 104 to 130 kg.

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

[3] The vitamin and trace mineral premix provided per kg of premix: 36.4 g Cu, 661 mg I, 242.5 g Fe, 73 g Mn, 661 mg Se, 242.5 g Zn, 5,291,088 IU vitamin A, 1,322,772 IU vitamin D, 26,455 IU vitamin E, 2,645 mg vitamin K, 24.3 mg vitamin B_{12}, 49,604 mg niacin, 16,534 mg pantothenic acid, and 4,960 mg riboflavin.

[4] Optiphos Plus (Huvepharma, Peachtree City, GA) provided 1,742 FTU/kg of diet for an estimated release of 0.11% STTD P.

[5] Potassium bicarbonate was included at 0 or 0.40% of the diet in all phases.

Table 2.2. Chemical analysis of diets (as-fed basis)

	Phase 1				Phase 2				Phase 3				Phase 4			
L-Lys HCl:	Low	Low	High	High	Low	Low	High	High	Low	Low	High	High	Low	Low	High	High
Item $KHCO_3$:	-[2]	+[2]	-	+	-	+	-	+	-	+	-	+	-	+	-	+
Calculated analysis																
Na^+, %	0.24	0.24	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Cl^-, %	0.38	0.38	0.42	0.42	0.38	0.38	0.42	0.42	0.37	0.37	0.42	0.42	0.37	0.37	0.41	0.41
K^+, %	0.92	1.11	0.78	0.98	0.80	0.99	0.66	0.86	0.74	0.93	0.59	0.79	0.68	0.87	0.53	0.73
DCAD[1]	230	281	182	232	199	249	151	201	184	234	133	183	169	220	118	169
Chemical analysis[3]																
DM, %	87.9	88.3	87.8	88.2	88.1	88.0	87.6	88.0	87.1	88.1	87.3	87.5	87.1	87.6	87.5	88.0
CP, %	19.7	19.4	16.7	16.6	18.4	18.2	16.3	15.9	16.1	15.7	13.1	13.4	14.0	14.8	11.5	12.2
Na^+, %	0.30	0.29	0.38	0.24	0.39	0.30	0.34	0.33	0.26	0.17	0.23	0.23	0.27	0.21	0.29	0.20
Cl^-, %	0.47	0.45	0.58	0.37	0.60	0.47	0.52	0.51	0.40	0.26	0.35	0.36	0.41	0.33	0.45	0.31
K^+, %	0.82	1.13	0.76	0.92	0.90	0.94	0.67	0.94	0.67	0.81	0.52	0.67	0.51	0.59	0.39	0.54
DCAD	210	289	194	235	231	240	171	240	171	207	133	171	130	151	100	138

[1] Dietary cation anion difference; calculated as $Na^+ + K^+ – Cl^-$, in mEq/kg diet.

[2] Potassium bicarbonate was included at 0% in diets without (-) $KHCO_3$ or 0.40% in diets with (+) $KHCO_3$ in all phases.

[3] Composite samples were submitted to Ward Laboratories, Inc. (Kearney, NE) for DM and CP analysis, as well as Kansas State University, Research and Extension Soil Testing Laboratory (Manhattan, KS) for mineral analysis.

Table 2.3. Effects of potassium bicarbonate with high and low crystalline lysine levels on growing-finishing pig performance[1]

	L-Lys HCl:	Low		High			P =		
Item	$KHCO_3$:	-[2]	+[2]	-	+	SEM	$KHCO_3$ × L-Lys HCl	L-Lys HCl	$KHCO_3$
BW, kg									
d 0		35.2	35.3	35.2	35.2	0.85	0.992	0.831	0.831
d 58		84.1	84.8	84.1	84.7	1.27	0.318	0.898	0.064
d 120		129.6	129.2	128.9	130.0	1.07	0.701	0.952	0.656
d 0 to 58									
ADG, kg		0.827	0.840	0.830	0.830	0.0074	0.184	0.433	0.126
ADFI, kg		1.703	1.717	1.717	1.707	0.0521	0.803	0.858	0.858
G:F		0.492	0.495	0.490	0.493	0.0134	0.718	0.623	0.298
d 58 to 120									
ADG, kg		0.739	0.724	0.734	0.739	0.0098	0.506	0.532	0.533
ADFI, kg		2.386	2.341	2.353	2.403	0.0276	0.218	0.544	0.917
G:F		0.310	0.310	0.312	0.308	0.0049	0.786	0.956	0.482
Overall (d 0 to 120)									
ADG, kg		0.783	0.782	0.782	0.785	0.0050	0.978	0.902	0.844
ADFI, kg		2.037	2.023	2.030	2.046	0.0260	0.705	0.574	0.947
G:F		0.385	0.387	0.386	0.384	0.0045	0.850	0.676	0.916
Carcass characteristics									
HCW, kg		96.8	96.7	96.5	96.6	0.769	0.988	0.767	0.959
Carcass yield, %		74.69	74.84	74.91	74.35	0.279	0.488	0.636	0.462
Backfat depth, cm[3]		1.64	1.62	1.65	1.67	0.029	0.392	0.154	0.872
Loin depth, cm		6.89	6.90	6.92	6.93	0.050	0.865	0.426	0.769
Lean, %		57.19	57.28	57.12	56.99	0.201	0.442	0.204	0.878

[1] A total of 1,944 pigs (PIC L337 × 1050, initially 35.2 ± 0.85, kg) were used in a 120-d study, split between 2 barns located at New Horizon Farms, Pipestone, MN, with 27 pigs per pen and 18 replicates per treatment.

[2] Potassium bicarbonate was included at 0% in diets without (-) $KHCO_3$ or 0.40% in diets with (+) $KHCO_3$ in all phases.

[3] Hot carcass weight served as a covariate for the analysis of backfat depth, loin depth, and lean, %.