Nutritional and management strategies to optimize growth performance and carcass traits of grow-finish pigs

by

Hilario Martin Cordoba

D.V.M., Universidad Nacional de Rio Cuarto, 2018

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

This dissertation is comprised of five chapters that evaluate feeder management prior to marketing and dietary interventions to improve carcass yield and reduce feed cost in finishing pigs. In Chapter 1, we implemented feed withdrawal of 12, 18, and 24 h prior to harvest to assess its effect on pig performance, carcass traits, and economic return over two marketing events. Feed withdrawal up to 24 h did not affect carcass characteristics of pigs in the first marketing event, nor did it affect the growth performance of the pigs remaining in the pen and marketed 14 d later. However, a reduction in hot carcass weight was observed in the final marketing event when pigs were withheld from feed for more than 18 h prior to harvest. Chapter 2 evaluated the effects of sulfate and hydroxychloride forms of copper, manganese, and zinc on growth performance, carcass characteristics, and body weight variation in finishing pigs. The use of manganese hydroxychloride, in comparison with the sulfate source, did not affect overall performance or carcass criteria. Similar growth performance was observed when the sulfate and hydroxychloride sources of copper, manganese, and zinc were compared; however, hot carcass weight tended to increase when hydroxychloride forms were used, compared to sulfate sources. Chapter 3 investigated finishing diets differing in Ca:P ratio, added phytase, and 25(OH)D3 levels on pigs' growth performance, body weight variability, serum 25(OH)D3, carcass characteristics, and bone characteristics. We observed that the lowest P level decreased growth performance, carcass weight, bone ash and strength. Also, a 1.1:1 Ca:P ratio reduced feed intake, bone ash and bone strength compared to a 1.25:1 ratio. While serum levels of vitamin D_3 increased when fed 25-hydroxy-D_3, no other benefits in growth performance or bone mineralization were observed. Chapter 4 developed predictive models of growth performance

and carcass characteristics of grow-finish pigs in response to dietary net energy using ingredient nutrient values from four different databases. The models demonstrate that increasing dietary NE increased growth performance and carcass responses, except for percentage lean which decreases as NE increased, across the four ingredient databases. Maintaining a Lys:NE ratio influenced the magnitude of change to NE in all responses evaluated as compared to when Lys:NE was not maintained. These models can improve our ability to predict the influence of dietary NE and other nutrients on pig performance and carcass criteria. Chapter 5 compares a central composite design and a factorial arrangement on their ability to predict pig growth performance when feeding variable net energy, soybean meal, and standardized ileal digestible lysine concentrations to pigs weighing 11 to 25 kg. The results showed that the predictors derived from the CCD experiment predicted the performance observed in the factorial arrangement experiment with an accuracy of ± 3% for almost all comparisons. We conclude that both the CCD and factorial arrangement demonstrated the importance of Lys to calorie and crude protein ratio on pig growth performance, indicating that both designs can provide similar results in swine nutrition research.

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Dedication

I dedicate this to everyone who has been a part of my journey, from my days in vet school to the completion of my Ph. D. program. Each of you has played a crucial role in helping me pursue and achieve my personal goals.

Preface

This dissertation is an original work completed by the author, Hilario M. Cordoba. Chapters 1 through 5 were formatted for publication according to the required standards of the Journal of Animal Science.

Chapter 1 - Evaluation of feeder management prior to marketing to improve carcass yield and reduce feed cost in finishing pigs

Abstract

Fasting pigs prior to harvest benefits food safety and pork quality at harvest. Studies have examined the effect of feed withdrawal prior to marketing applied on groups of pigs marketed at one time but not across multiple marketing events. Therefore, this study determined the effects of three feed withdrawal times before the first and final marketing event on pig performance, carcass traits, and economic return. A total of 695 finishing pigs (117.6 ± 1.06 kg) were allotted in a randomized complete block design and assigned to 1 of 3 treatments (24 pens per treatment; 9 to 10 pigs per pen). Treatments consisted of a total of 12, 18, or 24 h (including transportation and lairage) of feed withdrawal prior to harvest to determine its effects on hot carcass weight (HCW), carcass yield, and economics of pigs marketed at two different marketing events (3 heaviest pigs per pen marketed 14-d prior to the final marketing of all remaining pigs). There was no evidence of differences in growth performance during the 14-d period between marketing events. However, pigs with 24 h of feed withdrawal prior to harvest had lower ($P < 0.05$) live BW at the first marketing event and overall than pigs with 12 h of feed withdrawal. For carcass responses, pigs at the final marketing with 12 h of feed withdrawal prior to harvest had increased ($P < 0.05$) HCW compared to pigs with 24 h of feed withdrawal, leading to a tendency ($P = 0.055$) for increased HCW overall for the combined marketing events (0.5 kg heavier). When evaluating carcass yield using live weights at 24 h prior to harvest, pigs in the final marketing group with 12 h of feed withdrawal prior to harvest had greater yield ($P < 0.05$) than pigs marketed with 24 h of feed withdrawal; however, using live weights 12 h prior to harvest to

calculate yield, pigs with 24 h of feed withdrawal prior to harvest had increased yield ($P < 0.05$) compared to pigs marketed with 12 h of feed withdrawal for both marketing events. There were no differences in backfat, loin depth, and percentage lean between treatments. Feed consumed and cost were reduced ($P < 0.05$) with 24 h treatment compared to 12 h in the overall period. In conclusion, withholding feed at the first marketing event did not impact pigs' growth performance or HCW. However, carcass yield was affected by the feed withdrawal time prior to harvest, with greater HCW for pigs with 12 h compared to 24 h of feed withdrawal at the final marketing event.

Introduction

Finishing pigs inherently experience a period of feed deprivation during transport and lairage. Feed withdrawal prior to transportation to a processing plant reduces feed intake on the day of marketing and thereby reduces feed cost per pig (Kephart and Mills, 2005). Fasting also reduces gut fill, which ultimately reduces waste at the abattoir (Eikelenboom et al., 1991) and improves food safety by lowering the risk of carcass contamination with pathogenic microorganisms for humans (Fernandez, 2021).

Frobose et al. (2014) observed a linear reduction in hot carcass weight (HCW) with 8, 24, 26, and 48 h (including a total of 8 h of loading, transportation, and lairage) of feed removal prior to harvest, which resulted in a linear reduction of feed consumed the day of marketing as feed removal time increased. The HCW reduced 0.3 kg when feed withdrawal time was extended from 8 to 24 h, with reductions being at 2 kg or greater at or above 36 h of feed removal. This data was based on the last marketing of pigs, but to our knowledge no data is available on feed removal for the first group of pigs to be marketed (topped). With current feeder designs utilizing quick adjust settings, feeders could be closed to prevent pigs from eating prior to topping events

and then reset after pigs were marketed to supply feed to the remaining pigs in the pen. Thus, these first marketed pigs could benefit from a short feed removal prior to shipment.

This study aimed to determine the effects of feed withdrawal prior to marketing on pig performance, carcass traits, and economic return over two marketing events. We hypothesized that increased withholding feed time prior to marketing would reduce HCW and increase carcass yield, affecting economic outcomes. Additionally, we expected the feed withdrawal at the first marketing event would not be long enough to affect the performance of the pigs ho remain until the final marketing event.

Materials and Methods

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. This study was conducted at the Kansas State University Swine Teaching and Research Center in Manhattan, KS. The facility was totally enclosed and environmentally regulated, containing 36 pens in each barn. Each pen was equipped with a two-hole dry single-sided feeder (Farmweld, Teutopolis, IL) and a 1-cup waterer. Pigs were stocked at a floor space of approximately 0.65 m^2 per pig. Pens were equipped with adjustable gates to allow space allowances per pig to be maintained if a pig died or was removed from a pen during the experiment. Pens were located over a completely slatted concrete floor with a 1.22-m pit underneath for manure storage. A robotic feeding system (FeedPro; Feedlogic Corp., Wilmar, MN) was used to deliver and record daily feed additions to each individual pen.

Animals and diets

A total of 695 pigs (600 × 241, DNA; initially 117.6 ± 1.06 kg) were used in a 14-d study. Pigs were housed in mixed gender pens with 9 or 10 pigs per pen and 24 pens per

treatment. Pens of pigs were weighed 5-d prior to the start of the study and assigned to 1 of 3 treatments in a randomized complete block design with initial pen average weight as a blocking factor. Treatments consisted of none, 6, or 12 h of feeder closure prior to pig removal from pens at both the first and final (2 weeks after the first) marketing events to achieve approximately 12, 18 and 24 h of total feed withdrawal prior to harvest at the processing plant. Pigs were fed a corn-soybean meal-based diet that was formulated to meet or exceed nutrient requirements for pigs weighing 110 to 130 kg (NRC, 2012).

Pigs and feeders were weighed at the first and final marketing event at 8:30 h and 20:30 h to determine feed intake and individual BW within the marketing day, and to calculate ADG, ADFI, and G:F. Feed intake measurements also accounted for feed remaining in the pan after feeders were closed. Feeders from treatments with 18 and 24 h of feed withdrawal prior to harvest were closed at 14:30 h and 8:30 h, respectively, whereas feeders from the treatment with 12 h of feed withdrawal prior to harvest remained open. The total time without access to feed for all the treatments included 12 h of transportation and lairage time at the packing plant. Pigs were loaded out of barns at 20:30 h at each marketing event. At the first marketing event, the 3 heaviest pigs in each pen were selected for marketing and pens were adjusted to maintain stock density at 0.65 m^2 per pig.

Pigs were individually identified with an electronic tag and a tattoo for carcass data collection, transported to a USDA-inspected packing plant (Triumph Foods, St. Joseph, MO,) for harvest at 8:30 h the following day. Carcass measurements included HCW, loin depth, backfat, and percentage lean. Percentage lean was calculated from a plant proprietary equation. Carcass yield was calculated by dividing the pen average HCW by the individual live weight recorded in the morning (24 h before harvest and before feed withdrawal) and in the evening (12 h before

harvest after feed withdrawal treatments) of each marketing event. Feed cost was calculated using feed intake multiplied by a feed cost of $0.276/kg.

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 (version 4.4.1 (2021-08-10), R Foundation for Statistical Computing, Vienna, Austria) with pen considered as the experimental unit, initial weight as a blocking factor, and treatment as a fixed effect. The overall marketing data were analyzed by calculating a weighted average of the first and final marketing event for each response. The BW collected 24 h before harvest was used as covariate for analysis of HCW. Hot carcass weight was used as a covariate for backfat, loin depth, and percentage lean. Results were significant if *P*-values were ≤ 0.05 and considered tendencies if *P*-values were ≤ 0.10.

Results

For pig BW recorded 24 h before harvest, there was no evidence for differences ($P > 0.10$) between treatments at both marketing events and overall. However, at time of loadout (12 h before harvest), pigs enrolled on the 24 h of feed withdrawal prior to harvest treatment were lighter ($P < 0.05$) than those on the 12 h withdrawal prior to harvest, both at first marketing and for overall marketing data, but not for the final marketing event (Table 1). This was a result of pigs having different weight gain on each marketing day, with pigs on 12 h of feed withdrawal prior to harvest having greater gain ($P < 0.05$) than the other two treatments.

At the first marketing event, pigs BW loss was greater ($P < 0.05$) on 18 and 24 h of feed withdrawal prior to harvest compared to pigs on 12 h of feed withdrawal prior to harvest, but no differences ($P \geq 0.10$) were observed between the 18 and 24 h feed withdrawal strategies. At the final marketing event, pigs on 24 h feed withdrawal prior to harvest had increased ($P < 0.05$) BW

loss compared to the 12 and 18 h feed withdrawal strategies, but no differences were observed ($P \geq 0.10$) between the 12 and 18 h feed withdrawal treatments. However, when both marketing events were combined, pigs had greater ($P < 0.05$) BW loss as the time feed withdrawal prior to harvest increased.

For pig performance during the 14-d period between the first and final marketing event, there was no evidence of differences ($P \geq 0.10$) for any growth response criteria.

For carcass characteristics, there was no evidence for differences ($P > 0.10$) in HCW at the first marketing event. However, pigs at the final marketing event that had 12 h of feed withdrawal prior to harvest had increased ($P < 0.05$) HCW compared to those with 24 h of withdrawal prior to harvest (Table 2). When considering both marketing events, there was a tendency ($P = 0.055$) for a treatment effect with pigs having 12 h feed withdrawal prior to harvest having a 0.5 kg heavier HCW than those with 24 h feed withdrawal prior to harvest. When evaluating carcass yield using live weights for all pigs obtained 24 h prior to harvest, no differences ($P > 0.10$) were observed at the first marketing event, but pigs in the final marketing group with 12 h of feed withdrawal before harvest had increased carcass yield ($P < 0.05$) compared to pigs with 24 h of feed withdrawal before harvest. However, when evaluating carcass yield using live weights obtained at load out (12 h prior to harvest) at the first marketing event, pigs with 24 h of feed withdrawal prior to harvest had increased ($P < 0.05$) carcass yield compared to only the pigs with 12 h feed withdrawal prior to harvest. At the final marketing event and overall, pigs with 24 h of feed withdrawal prior to harvest had increased yield ($P < 0.05$) compared with the other two treatments. There were no differences in backfat depth, loin depth, and percentage lean observed between treatments ($P > 0.10$).

For feed consumed and feed cost, in the first marketing event, pigs marketed with 12 h feed withdrawal prior to harvest had increased ($P < 0.05$) feed consumption and feed cost compared to those with 18 h feed withdrawal, with pigs marketed with 24 h feed withdrawal prior to harvest having the lowest ($P < 0.05$) feed consumption and feed cost. This represents 1.47 and 0.71 kg less feed consumed per pig between the 12 and 18 h treatment, respectively, in comparison with the 24 h treatment. On the final marketing event and overall, feed consumed and feed cost per pig were increased ($P < 0.05$) for pigs marketed with 12 or 18 h of feed withdrawal before harvest compared to those with 24 h feed withdrawal prior to harvest, which accounts for a total feed intake reduction of 1.14 kg between the 12 and 24 h treatments, representing $0.32 per pig in the overall period.

Discussion

Reducing accessibility to feed prior to harvest decreases feed consumed during the marketing day resulting in reduced pigs' body weight due to emptying the gastrointestinal tract (Driessen et al., 2020). This was demonstrated by Frobose et al. (2014), who used 8, 24, 36, and 48 h of feed withdrawal prior to harvest in a commercial facility and observed a linear reduction in feed consumed during the marketing day as feed withdrawal time increased, resulting in a linear reduction in HCW and carcass yield. In our study, feed withdrawal was established to understand the effect of carcass and economic responses using 12, 18, and 24 h of feed restriction prior to harvest where transportation and lairage time were considered. In previous studies, feed withheld for 24 h prior to harvest resulted in lighter pigs than those that had accessibility to feed for 12 h prior to harvest including transportation and lairage time (Jones et al., 1985; Bertol et al., 2005; Panella-Riera et al., 2012). The same response was observed in our study, where pigs' BW decreased as feed withdrawal time increased from 12 to 24 h in the first

marketing event and when overall data was summarized. However, in the final marketing event, even though there was a difference of 2.1 kg of BW between pigs without access to feed for 24 h compared to 12 h, the difference was not significant. The reason for these results might be related to the season of the year and the procedures during each marketing day. Daily temperature was elevated during the final marketing day as compared to the first marketing event, which likely reduced feed intake of pigs with accessibility to feed before loading out on the final marketing day.

Another difference between our study and those observed by others may be that we maintained 0.65 m^2 per pig for the remaining 14 d from the first and last marketing events by adjusting available floor space. In a commercial facility, after removing the 10 to 20% heaviest pigs in a pen, floor and feeder space allowance is increased which helps to avoid growth restriction. This was demonstrated by Flohr et al. (2016) who used three marketing events providing 0.65 m^2 per pig and removed pigs as space became constrained to not restrict growth based on Gonyou et al. (2006) allometric equations. In our study, after removing the 3 heaviest pigs at the first marketing event, the front gate of each pen was adjusted to keep the initial 0.65 m^2 per pig. This practice allows us to see the effect of feed withdrawal and avoid having a space allowance effect.

Morrow et al. (2002) conducted a study marketing finishing pigs at three different times to see the effect on carcass composition, but they did not measure growth performance of the pigs between each marketing event. To our knowledge, there is limited data in the literature showing results for growth performance between marketing events in the same group of pigs. In this study, our results showed that reducing in-barn feed accessibility at the first marketing event

for up to 12 hours did not affect the performance of the pigs remaining in the pens for the next 14 d until marketed.

The HCW in the first marketing was not different between the three durations of feed withdrawal. These results were not expected because feeders were shut down to accomplish the feed withdrawal time and the feed intake decreased as the time of feed withdrawal increased. However, at the final marketing event, the results showed the feed restriction response in gain and HCW. Pigs having access to feed increased gain during the marketing day, and that was reflected in the HCW results. When results observed at the first and final marketing event were combined, a tendency for a marginal increase in HCW of 0.5 kg was observed when pigs had access to feed for 12 h before being harvested in comparison to those without for 24 h prior to harvest. These results agree with results of Fàbrega et al. (2019), Frobose et al. (2014), and Faucitano et al. (2006) where HCW decreased as the time of feed withdrawal prior to harvest increases.

In this study, pigs were weighed individually before and after the fasting period. When carcass yield was calculated using the live weights before the period of feed withdrawal, carcass yield increased when pigs had 12 h of feed withdrawal compared to those with 24 h at the final marketing event. This is a result of HCW loss after the feed withdrawal period prior to harvest. In contrast, when carcass yield was calculated using the BW recorded after the fasting period, carcass yield increased for those pigs with 24 h of feed withdrawal compared to those with 12 h at the final marketing event and overall. This is a result of the gut fill at the time BW was recorded which affected carcass yield. Similar results were observed by Frobose et al. (2014) when feed was withdrawn for 8, 24, 36, and 48 h prior to harvest, where carcass yield increased as the time without access to feed increased. Nonetheless, these results were different from those

observed by Kephart and Mills (2005), Jones et al. (1985), Eikelenboom et al. (1991) and Faucitano et al. (2006) who applied between 0 to 48 h of feed withdrawal and did not find differences in carcass yield over 24 h of feed withdrawal.

Backfat depth, loin depth, and percentage of lean were analyzed to determine the effect of feed withdrawal prior to harvest. Some authors Morrow et al. (2002) and Leheska et al. (2003) reported no differences in those carcass traits when having 12 to 48 h of feed withdrawal. However, with the decrease in HCW observed in past literature and with current fast growth genetics (Frobose et al., 2014), it is important to evaluate if feed withdrawal also affects carcass characteristics. The results of our study showed that feed withdrawal time used did not affect backfat, loin depth, and percentage of lean at any marketing event and overall.

Frobose et al. (2014) observed savings of 5 kg of feed per pig during the time prior to marketing when feed was withdrawn for 48 h compared to 8 h. A linear response on feed savings was observed in our study as the time of feed withdrawal increased. At the first marketing event, pigs without access to feed for 24 h and 18 h reduced feed consumption by 1.47 and 0.71 kg, respectively, compared to pigs withheld for 12 h. However, at the final marketing event the feed intake results were different. There was a reduction in feed consumption for pigs with 24 h of feed withdrawal compared to the 12 and 18 h treatments, but no differences in feed intake between pigs with feed withdrawn for 12 and 18 h, even though pigs had 6 h more of feed access. This could be a result of the high summer temperatures during the second marketing day, reducing the desire for pigs to consume feed. The feed cost calculation is directly tied to the feed intake response. Therefore, it is necessary to consider if the savings in feed cost will offset the losses in HCW. The level of HCW loss will be dependent on the total time without access to feed from in-barn feeder closure and including transportation and lairage period.

Conclusion

This data showed that after removing the 3 heaviest pigs from each pen in the first marketing event, there were no effects of feed withdrawal at different times prior to harvest on growth performance of the pigs that stayed until the end of the study nor was there any effect on HCW, carcass yield, and economics for pigs marketed at the first marketing event. However, at the final marketing event and overall, differences in HCW, carcass yield, and economics were observed. These data suggest that feed withdrawal time greater than 18 h reduces HCW. Therefore, reduced feed cost will have to offset potential losses in HCW when times of feed withdrawal exceed 18 h prior to harvest. In addition, the time without access to feed should consider the duration of feed withdrawal as well as transportation and lairage times. Therefore, knowing the duration of transportation and lairage is crucial to properly apply feed withdrawals prior to harvest.

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Table 1.1. Effects of withholding feed prior to harvest on growth performance[1]

	Feed withdrawal time before harvest, h[2]				
Item	12	18	24	SEM	*P* =
BW, kg					
24 h before harvest					
First marketing	126.4	125.6	124.7	1.19	0.334
Final marketing	127.3	127.2	127.1	1.21	0.994
Overall[3]	126.9	126.7	126.5	1.08	0.850
12 h before harvest (at time of loading on the truck)					
First marketing	127.4[a]	125.2[ab]	123.9[b]	1.10	0.003
Final marketing	127.6	127.1	125.5	1.27	0.153
Overall[3]	127.4[a]	126.4[ab]	125.1[b]	1.11	0.020
BW change, kg/pig[4]					
First marketing	1.13[a]	-0.49[b]	-0.86[b]	0.444	< 0.001
Final marketing	0.31[a]	-0.15[a]	-1.67[b]	0.200	< 0.001
Overall	0.57[a]	-0.26[b]	-1.43[c]	0.222	< 0.001
Overall (d 0 to 14)					
ADG, kg	0.99	0.98	0.95	0.032	0.528
ADFI, kg	2.84	2.84	2.85	0.029	0.997
G:F	0.35	0.35	0.34	0.011	0.439

[1]A total of 695 mixed sex pigs (initial BW 117.6 ± 1.06 kg) were used in a 14-d trial with 24 replications per treatment.

[2]The 3 treatments consisted of none, 6, or 12 h of feeder closure prior to loading on the truck at both the first marketing event (2 weeks before final marketing) and final marketing event to achieve 12, 18 and 24 h, respectively, of total feed withdrawal prior to harvest.

[3]Weighted average from the first and final marketing.

[4]Body weight difference between the 24 h and 12 h before harvest weight determination.

Table 1.2. Effects of withholding feed prior to harvest on carcass characteristics[1]

Item	Feed withdrawal time prior to harvest, h[2]			SEM	*P* =
	12	18	24		
Carcass characteristics					
HCW, kg[3]					
First marketing	92.4	92.2	92.6	0.41	0.573
Final marketing	93.6[a]	93.3[ab]	92.8[b]	0.17	0.010
Overall[4]	93.2	93.0	92.7	0.20	0.055
Carcass yield, %					
24 h before harvest					
First marketing	73.8	73.6	73.8	0.30	0.686
Final marketing	73.4[a]	73.2[ab]	72.9[b]	0.10	0.010
Overall[4]	73.5	73.3	73.1	0.20	0.099
12 h before harvest					
First marketing	73.1[b]	73.8[ab]	74.3[a]	0.30	0.012
Final marketing	73.2[b]	73.3[b]	73.8[a]	0.10	0.003
Overall[4]	73.2[b]	73.5[b]	73.9[a]	0.10	< 0.001
Backfat, mm[5]					
First marketing	13.5	13.3	13.2	0.21	0.572
Final marketing	13.9	13.7	14.1	0.17	0.259
Overall[4]	13.7	13.6	13.8	0.14	0.449
Loin depth, mm[5]					
First marketing	65.9	67.0	66.1	0.55	0.945
Final marketing	65.5	65.5	64.8	0.36	0.254
Overall[4]	65.6	65.7	65.2	0.31	0.492
Lean, %[5]					
First marketing	56.0	56.1	56.2	0.20	0.703
Final marketing	55.7	55.8	55.5	0.10	0.136
Overall[4]	55.8	55.9	55.7	0.10	0.372
Feed consumed, kg/pig[6]					
First marketing	1.56[a]	0.80[b]	0.09[c]	0.096	< 0.001
Final marketing	1.12[a]	1.19[a]	0.14[b]	0.079	< 0.001
Overall[4]	1.26[a]	1.07[a]	0.12[b]	0.069	< 0.001
Feed cost, $/pig[7]					
First marketing	0.43[a]	0.22[b]	0.03[c]	0.026	< 0.001
Final marketing	0.31[a]	0.33[a]	0.04[b]	0.022	< 0.001
Overall[4]	0.35[a]	0.29[a]	0.03[b]	0.019	< 0.001

[1]A total of 695 mixed sex pigs (initial BW 117.6 ± 1.06 kg) were used in a 14-d trial with 24 replications per treatment.

[2]The 3 treatments consisted of none, 6, or 12 h of feeder closure prior to loading on the truck at both the first marketing event (2 weeks before final marketing) and final marketing event to achieve 12, 18 and 24 h, respectively, of total feed deprivation prior to harvest.

[3]24 h BW before harvest was used as a covariate for analysis of HCW.

[4]Weighted average from the first and final marketing.

[5]HCW was used as a covariate for analysis of backfat, loin depth, and percentage lean.

[6]Feed consumed the day of marketing (24 h and 12 h before harvest).

[7]Feed consumed between 24 h and 12 h before harvest multiplied by a diet cost of $0.276/kg.

Chapter 2 - Effect of sulfate or hydroxychloride forms and levels of copper, manganese, and zinc on growth performance, carcass characteristics, and body weight variation of finishing pigs

Abstract

Two experiments were conducted to evaluate the effect of source and levels of Cu, Mn, and Zn on the performance, carcass characteristics, and body weight (BW) variability of finishing pigs. Experiment 1 used 2,025 pigs (337 × 1050, PIC; initially 39.9 ± 1.22 kg) with 27 pigs per pen and 15 pens per treatment. Treatments consisted of a control diet containing 30 mg/kg of Mn from $MnSO_4$ (Eurochem, Veracruz, Mexico) or 15, 30, 45, or 65 mg/kg of Mn from Mn hydroxychloride (IBM; IntelliBond M, Selko, USA, LLC, Indianapolis, IN). From d 0 to 43, gain:feed ratio (G:F) increased (quadratic, $P = 0.035$) when Mn hydroxychloride increased up to 45 mg/kg but then decreased thereafter. There was no evidence for difference from increasing Mn hydroxychloride for any growth response criteria in the overall period. When comparing Mn sources at 30 mg/kg of added Mn, there was no evidence of differences in any period or overall growth performance or carcass characteristics. In Exp.2, 1,026 pigs (337 × 1050, PIC; initially 25.9 ± 0.33 kg) were used with 27 pigs per pen and 19 pens per treatment. Treatments consisted of a control diet containing 110, 16, and 150 mg/kg of added Zn, Mn, and Cu, respectively, from sulfate sources or the same concentrations provided by hydroxychloride sources (IntelliBond, Selko USA, LLC, Indianapolis, IN). From d 0 to 61, there was a tendency ($P = 0.052$) for increased G:F when sulfate forms of Cu, Mn, and Zn were fed. From d 61 to 124, pigs fed hydroxychloride mineral sources had increased ($P = 0.041$) ADG compared with those fed sulfate sources. However, there was no evidence for a difference in overall growth

performance. A tendency ($P = 0.054$) for increased hot carcass weight (HCW) was observed in the final marketing event when pigs were fed hydroxychloride forms of minerals, but no evidence of differences was observed in the first marketing or when all marketing data was combined. In both experiments, pigs were individually weighed to determine within pen BW coefficient of variation (CV). There were no evidence of differences in BW variability. In conclusion, feeding hydroxychloride sources of Cu, Mn, and Zn resulted in no differences in overall growth performance and carcass characteristic compared with feeding sulfate sources; however, the G:F improvement when Mn hydroxychloride was increased up to 45 mg/kg and the tendency to increase HCW when feeding Cu, Mn, and Zn hydroxychloride warrants further investigation.

Introduction

Trace minerals are essential components of organs and tissues, and play diverse roles in the body (NRC, 2012). They are involved in functions such as cell replication, signaling, and enzymatic reactions in carbohydrate, lipid, and protein metabolism (Suttle, 2010). Manganese, a trace mineral necessary for reproduction and growth, is a component of superoxide dismutase and chondroitin sulfate synthesis (NRC, 2012). Zinc is involved in many enzymatic reactions as a component of metalloenzymes, cell signaling, and hormonal activity such as insulin (NRC, 2012). Copper is important for the synthesis of hemoglobin and red blood cells and activates several oxidative enzymes. It also promotes growth when feeding above requirement estimates (Espinosa, 2019).

These minerals have relatively low bioavailability in feed ingredients typically used in swine diets (NRC, 2012); therefore, trace mineral premixes are added to the diet. Due to their

low cost, sulfate forms have been the preferred source to use for several years (Shurson et al., 2011).

Hydroxychloride trace minerals are also inorganic forms recently introduced to the feed industry (Reddy et al., 2021). They are bound to hydroxy and chloride groups rather than carbon ligands like organic minerals. This binding ensures that they only dissociate at low pH levels, such as those found in the stomach or the upper portion of the small intestine. Consequently, hydroxychloride forms have less interaction with other minerals in the upper gastrointestinal tract than other inorganic mineral sources (Reddy et al., 2021).

According to NRC (2012), the requirement estimates for Cu, Mn, and Zn are 4 to 3 mg/kg, 2 mg/kg, and 60 to 50 mg/kg, respectively, from 25 to 135 kg of body weight (BW). A survey by Faccin et al. (2023) observed that the US industry uses on average 15, 12, and 2 times more than the NRC (2012) requirement estimates of Cu, Mn, and Zn, respectively, in swine diets from 25 to 135 kg BW. The reason for feeding high concentrations of these trace minerals is to provide a margin of safety as many requirements studies date back to the 1960's and 1970's (Oberleas et al., 1962; Dahmer et al., 1972). In addition, recent studies observed that feeding Zn and Cu above NRC (2012) requirement estimates improved growth performance and hot carcass weight (HCW) of finishing pigs (Coble et al., 2017; Cemin et al., 2019b; Espinosa, 2019).

In both experiments, we hypothesized that different concentrations of Mn hydroxychloride, and the hydroxychloride forms of Cu, Mn, and Zn would provide improvements in growth performance and carcass characteristics compared to inorganic forms of these minerals. To test our hypothesis, these studies evaluated the effects of increasing Mn from Mn hydroxychloride compared to a diet formulated to contain commercial concentrations of Mn from Mn sulfate. We also compared a feeding program using either sulfate or hydroxychloride

mineral forms of Mn, Zn, and Cu on growth performance, carcass characteristics, and weight variation of finishing pigs housed in a commercial environment.

Materials and Methods

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocols used in these experiments.

Animals and diets

Two studies were 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 totally slatted floors. Each pen (3.05 × 5.49 m) was equipped with a 5-hole stainless steel dry self-feeder (Thorp Equipment, Thorp, WI) and a bowl waterer for *ad libitum* access to feed and water. The first experiment was conducted from August 23, 2021 to November 26, 2021, and the second experiment was conducted from June 19, 2022 to November 20, 2022. All treatment diets were manufactured at the New Horizon Farms Feed Mill in Pipestone, MN, and were formulated to meet or exceed NRC (2012) requirement estimates for growing-finishing pigs for their respective weight ranges (Table 1 and 2). Daily feed additions to each pen were accomplished using a robotic feeding system (FeedPro; Feedlogic Corp., Wilmar, MN) able to record feed deliveries for individual pens. Pens of pigs were weighed approximately every 14 d to determine average daily gain (ADG), average daily feed intake (ADFI), and gain-to-feed ratio (G:F). On the last day of each trial, final pen weights were obtained, and pigs were tattooed with a pen identification number and transported to a U.S. Department of Agriculture-inspected packing plant (JBS Swift, Worthington, MN) for carcass data collection. Carcass

measurements included HCW, loin depth, backfat depth, and percentage lean. Loin depth and backfat depth were measure by optical probe (SFK; Herlev, Denmark). Percentage lean was calculated from a plant proprietary equation. Carcass yield was calculated by dividing the pen average HCW by the pen average final live weight obtained at the farm.

Experiment 1

A total of 2,225 pigs (337 × 1050, PIC; initially 39.9 ± 1.22 kg) were used in a 95-d growth trial. Pigs were housed in mixed gender pens with 27 pigs per pen and 15 pens per treatment. The treatments were structured as a completely randomized design and consisted of a control diet containing 30 mg/kg of Mn from $MnSO_4$ (Eurochem, Veracruz, Mexico) or 15, 30, 45, or 65 mg/kg of Mn from Mn hydroxychloride (IBM; IntelliBond M, Selko USA, LLC, Indianapolis, IN). Diets were fed in meal form with phase 1 fed from 39.9 to 49.9 kg, phase 2 from 49.9 to 74.8 kg, phase 3 from 74.8 to 99.8 kg, and phase 4 from 99.8 to 133.3 kg. Experimental diets were corn-soybean meal-dried distiller grain with solubles (DDGS)-based and were formulated using a premix without Mn. All diets contained 150 mg/kg of Cu from IntelliBond C (Selko, Indianapolis, IN) and 100 mg/kg of Zn from IntelliBond Z (Selko, Indianapolis, IN). Manganese sources were added to the diet by hand-made premixes, which were added at the expense of corn.

On d 78, all pigs were individually weighed to determine BW variation. The same day, the 3 heaviest pigs in each pen were selected and marketed. These pigs were included in the calculation of pen growth performance, but not the carcass characteristics.

Experiment 2

A total 1,026 pigs (337 × 1050, PIC; initially 25.9 ± 0.33 kg) were used in a 124-d growth trial. Pigs were housed in mixed gender pens with 27 pigs per pen and 19 pens per treatment. Treatments were structured as a completely randomized design and consisted of a control diet containing 110, 16, and 150 mg/kg of added Zn, Mn, and Cu, respectively, from sulfate sources or the same concentrations provided by hydroxychloride sources (IntelliBond, Selko USA, LLC, Indianapolis, IN). Diets were corn-soybean meal-DDGS-based and fed in meal form with phase 1 fed from 26 to 49.9 kg, phase 2 from 49.9 to 74.8 kg, phase 3 from 74.8 to 99.8 kg, and phase 4 from 99.8 to 136.8 kg.

On d 0 and 102, all the pigs in each pen were individually weighed to determine BW variation. On d 102, the 6 heaviest pigs in each pen were selected, tattooed with a pen identification number, and transported to the packing plant for carcass data collection. For this experiment, carcass characteristics were collected at the first and final marketing event for evaluation of the individual events and overall. The individual HCW collected at the packing plant was analyzed to determine variation within and between treatments.

Chemical analysis

For both experiments, representative diet samples were collected from all the feeders of each treatment by phase and stored at -20°C until analysis. Samples of the diets were combined within the dietary treatment and composite samples per treatment and phase were sent to a commercial laboratory (Cumberland Valley Analytical Services, Waynesboro, PA) where they were analyzed for dry matter (method 935.29; Association of Official Agricultural Chemists (AOAC) International, 1990), crude protein (990.03, AOAC International, 1990), calcium (Ca)

and phosphorus (P; method 985.01; AOAC International, 1990), Cu, Zn, and Mn (Method 985.01; AOAC International, 2000).

Statistical analysis

Data from both studies were analyzed as a completely randomized design for one-way ANOVA using the lmer function from the lme4 package in R (version 4.1.1 (2021-08-10), R Foundation for Statistical Computing, Vienna, Austria) with pen considered the experimental unit, and treatment as fixed effect. For Experiment 1, contrast coefficients were used to evaluate linear and quadratic effects of Mn concentration within the hydroxychloride form and pairwise comparison of Mn sources at 30 mg/kg. In both experiments, pig individual weight data on d 78 (Exp. 1) and d 0 and 102 (Exp.2) were used to calculate within-pen coefficient of variation which was analyzed in a similar manner to growth data. Hot carcass weight was used as covariate for carcass characteristics analysis. All results were considered significant at $P \leq 0.05$ and marginally significant between $P > 0.05$ and $P \leq 0.10$.

Results and Discussion

Chemical analysis

Considering the trace minerals from basal ingredients, analyzed dietary Cu, Mn, and Zn were consistent with calculated values used in diet formulation in both experiments (Table 3 and 4).

Growth performance and carcass characteristics

In Exp.1, from d 0 to 43, G:F increased (quadratic, $P = 0.035$) with increasing Mn hydroxychloride up to 45 mg/kg but then decreased thereafter (Table 5). There was no evidence for difference ($P \geq 0.10$) from increasing Mn hydroxychloride for any growth response criteria

from d 43 to 95 or d 0 to 95. When comparing Mn sources at 30 mg/kg added Mn, there was no evidence of differences ($P \geq 0.10$) in any period or for overall growth performance. For carcass characteristics, no evidence of difference ($P \geq 0.10$) was observed for any criteria when comparing pigs fed increasing Mn hydroxychloride or either Mn source in diets at 30 mg/kg.

Kerkaert et al. (2021) observed that feeding 8, 16, and 32 mg/kg of Mn from Mn sulfate or hydroxychloride during the finisher period resulted in no differences in growth performance. Some studies have observed increased or tendencies to increase G:F in the grower (35 to 70 kg) stage (Kats et al., 1994; Apple et al., 2004; Sawyer et al., 2007), but not in others (Schwarz et al., 2017). Based on our findings and others, G:F appears to be improved in the early stages of the finishing period with increasing inclusion of Mn, but not for the entire finishing phase. Studies using different sources and levels of added Mn did not observe evidence for differences in carcass characteristics (Kats et al., 1994; Sawyer et al., 2007; Schwarz et al., 2017). However, Kerkaert et al. (2021) observed a tendency for a quadratic increase in carcass yield when increasing added Mn from Mn hydroxychloride from 8 to 16 mg/kg, but a decrease thereafter. This response was not observed in our study as the lowest concentration was 15 mg/kg of added Mn.

In Exp. 2, from days 0 to 61, there was a tendency ($P = 0.052$) for increased G:F when sulfate forms of Cu, Mn, and Zn were fed while from d 61 to 124, pigs fed hydroxychloride mineral sources had increased ($P = 0.041$) ADG (Table 6). However, there were no differences in growth performance in the overall (d 0 to 124) finishing period. No evidence of difference ($P > 0.10$) was observed for any carcass criteria when comparing pigs fed sulfate or hydroxychloride mineral sources at the first marketing event. However, there was a tendency ($P = 0.054$) for increased HCW in the final marketing event when pigs were fed hydroxychloride

forms of minerals, although when both marketing events were combined, no evidence of differences ($P > 0.10$) was observed.

Mendonça et al. (2021) observed improvements in ADG, individual BW, and HCW when feeding 150 and 80 mg/kg of added Cu and Zn hydroxychloride, respectively, compared to the same levels provided by CuSO4 and ZnO to pigs from 27.7 to 104 kg. Hernández et al. (2008) observed improvements in G:F when using proteinate amino acid chelate forms of Zn and Cu compared to sulfate sources from 25 to 107 kg. In addition, a meta-analysis of six different trials reported improvements in ADG and G:F when using 80 mg/kg of Zn from hydroxychloride forms compared to sulfate forms (Van Kuijk et al., 2019). Improvements in ADG, ADFI, G:F, final BW, and HCW were observed by Knauer and Van de Ligt (2022) when using 150 mg/kg of added Cu hydroxychloride in comparison with another hydroxychloride form of Cu. The results from the cited literature show responses on growth performance and carcass traits in some of the studies and at certain stages of growth. However, like in our study, most studies showed no benefit of using an alternative source compared to sulfates when supplementing minerals from 19 to 133 kg (Creech et al., 2004; Cemin et al., 2019a; Kerkaert et al., 2021).

Mendonça et al. (2021) observed improvements in ADG, final BW, and HCW when using 150 mg/kg of added Cu hydroxychloride compared to the same levels provided by $CuSO_4$. In addition, despite the lack of significance, Coble et al. (2017) observed 2.2 kg greater HCW when using 150 mg/kg of Cu hydroxychloride compared to the same level provided by $CuSO_4$. This is similar to the improvement from hydroxychloride forms over the sulfate forms in ADG observed during the finisher period in our study and the tendency for heavier HCW at the final marketing. However, it cannot be only attributed to a single mineral because there are other

studies that also determined the Zn responses on ADG and HCW (Cemin et al., 2019b; Van Kuijk et al., 2019; Villagómez-Estrada et al., 2021).

Body and hot carcass weight variation

There was no evidence of difference in the CV of pig BW between treatments at d 78 in Exp. 1 and on d 0 or d 102 of Exp. 2 (Tables 5 and 6). For HCW variability, no evidence of difference was observed when comparing sulfates and hydroxychloride mineral sources in pigs evaluated on the first, final, and combined marketing events.

Pigs have an inherent decrease in BW variability from birth to market when expressed as CV (Tolosa et al., 2021). In a meta-analysis of pig BW variation from birth to market, Tolosa et al. (2021) observed BW CV was approximately 21% and 10% at birth and marketing, respectively. Some authors studied reducing pigs' BW CV by sorting pens by weight categories (O'Quinn et al., 2000; Brumm et al., 2002; Wolter et al., 2002; Hastad et al., 2020); however, we are not aware of any studies that evaluated mineral source or level on pig body weight variability. Our results demonstrate that using different levels and sources of Mn or sources of Cu, Mn, and Zn, did not affect the CV of pig BW.

Conclusion

In conclusion, these results suggest that increasing levels of Mn hydroxychloride or using hydroxychloride forms of Cu, Mn, and Zn together in growing-finishing pig diets did not improve overall growth performance and carcass characteristics compared with those fed sulfate forms. Providing 30 mg/kg of Mn from Mn sulfate or hydroxychloride forms did not result in differences in any of the traits evaluated. However, the improvement in G:F observed during the grower period on Exp. 1 when Mn hydroxychloride was increased up to 45 mg/kg warrants further investigation as a potential benefit for growth performance and carcass traits.

Additionally, the tendency to increase HCW when feeding hydroxychloride forms of Cu, Mn, and Zn on pigs marketed at the end of the study warrants further investigation.

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Table 2.1. Composition of experimental diets, Exp. 1 (as-fed basis)[1]

Item	Phase 1	Phase 2	Phase 3	Phase 4
Ingredient, %				
Corn	58.41	66.40	72.29	80.38
Soybean meal, 47.7% CP	26.75	19.06	13.41	15.46
DDGS[2]	10.00	10.00	10.00	---
Corn oil	1.50	1.50	1.50	1.50
Limestone	1.23	1.10	1.10	0.90
Monocalcium P, 21% P	1.10	0.95	0.70	0.80
Salt	0.35	0.35	0.35	0.35
L-Lys-HCl	0.37	0.38	0.39	0.30
DL-Met	0.06	0.03	0.01	0.04
L-Trp	0.02	0.02	0.03	0.03
Thr[3]	0.10	0.09	0.10	0.12
Vitamin-trace mineral premix[4,5]	0.10	0.10	0.10	0.10
Phytase[6]	0.02	0.02	0.02	0.02
Mn source[7]	+/-	+/-	+/-	+/-
TOTAL	100	100	100	100
Calculated analysis				
Standardized ileal digestible (SID) AA, %				
Lys	1.15	0.97	0.84	0.79
Ile:Lys	63	61	60	61
Leu:Lys	140	148	155	147
Met:Lys	31	29	29	32
Met and Cys:Lys	55	55	56	59
Thr:Lys	62	62	64	65
Trp:Lys	19	19	19	20
Val:Lys	70	70	70	70
His:Lys	42	42	42	43

Total Lys, %	1.31	1.11	0.96	0.89
NE, kcal/kg	2,499	2,550	2,586	2,605
SID Lys:NE, g/Mcal	4.62	3.82	3.25	3.04
CP, %	20.9	17.8	15.6	14.4
Ca, %	0.73	0.63	0.57	0.53
STTP, %[8]	0.52	0.47	0.41	0.39

[1]Phases 1, 2, 3, and 4 were fed from 39.9 to 49.9 kg, 49.9 to 74.8 kg, 74.8 to 99.8 kg, and 99.8 to 133.3 kg, respectively.

[2]DDGS, dried distiller grains with solubles.

[3]Thr Pro; CJ America-Bio, Downers Grove, IL.

[4]Provided per kg of diet: 110 mg Fe, 0.30 mg I, 0.30 mg Se, 1,089 IU vitamin A, 272 IU vitamin D, 5.4 IU vitamin E, 1.2 mg vitamin K, 22.5 mg niacin, 7.5 mg pantothenic acid, 2.25 mg riboflavin, and 11 µg vitamin B12.

[5]Tribasic copper chloride (IntelliBond C, Selko, Indianapolis, IN) provided 150 mg/kg of Cu and Zinc hydroxychloride (IntelliBond C, Selko, Indianapolis, IN) provided 100 mg/kg of Zn.

[6]Optiphos Plus 2500 G (Huevepharma, Sofia, Bulgaria) was included at 1,500 FTU/kg providing an estimated release of 0.14% STTD P in all the feed phases.

[7]Mn hydroxychloride (IntelliBond M, Selko, Indianapolis, IN) or Mn sulfate ($MnSO_4$, Eurochem, Veracruz, Mexico).

[8] STTD P, standardized total tract digestible phosphorus.

Table 2.2. Composition of experimental diets, Exp. 2 (as-fed basis)[1]

Item	Phase 1	Phase 2	Phase 3	Phase 4
Ingredient, %				
Corn	54.63	60.98	65.87	68.37
Soybean meal, 47.7% CP	17.34	11.20	6.68	4.22
DDGS[2]	25.00	25.00	25.00	25.00
Limestone	1.45	1.40	1.30	1.25
Monocalcium P, 21% P	0.30	0.20	---	---
Salt	0.40	0.40	0.40	0.40
L-Lysine-HCl	0.48	0.45	0.43	0.43
DL-Methionine	0.02	---	---	---
L-Tryptophan	0.03	0.03	0.03	0.04
Threonine[3]	0.11	0.08	0.07	0.08
Vitamin-trace mineral premix[4]	0.20	0.20	0.20	0.20
Phytase[5]	0.05	0.05	0.03	0.02
TOTAL	100	100	100	100
Calculated analysis				
Standardized ileal digestible (SID) AA, %				
Lys	1.08	0.91	0.78	0.72
Ile:Lys	60	60	60	60
Leu:Lys	155	168	183	190
Met:Lys	29	30	33	34
Met and Cys:Lys	56	59	64	66
Thr:Lys	62	62	63	65
Trp:Lys	18	18	18	18
Val:Lys	71	73	76	77
His:Lys	42	44	46	47
Total Lys, %	1.27	1.08	0.94	0.87
NE, kcal/kg	2,383	2,423	2,458	2,474
SID Lys:NE, g/Mcal	4.53	3.76	3.17	2.91

CP, %	20.4	17.9	16.1	15.2
Ca, %	0.67	0.62	0.53	0.50
STTP, %[6]	0.43	0.39	0.33	0.31

[1]Phases 1, 2, 3, and 4 were fed from approximately 25.9 to 49.9 kg, 49.9 to 74.8 kg, 74.8 to 99.8 kg, 99.8 to 137 kg, respectively.

[2]DDGS, dried distiller grains with solubles.

[3]Thr Pro; CJ America-Bio, Downers Grove, IL.

[4] Provided per kg of diet: 110 mg Fe, 0.30 mg I, 0.30 mg Se, 1,089 IU vitamin A, 272 IU vitamin D, 5.4 IU vitamin E, 1.2 mg vitamin K, 22.5 mg niacin, 7.5 mg pantothenic acid, 2.25 mg riboflavin, 11 µg vitamin B12 and 110 mg/kg of Zn, 16 mg/kg of Mn, and 150 mg/kg of Cu provided by sulfate sources or hydroxychloride sources (IntelliBond, Selko, Indianapolis, IN) were added to form the experimental treatments.

[5]Optiphos (Huevepharma, Sofia, Bulgaria) was included at 1,250 FTU/kg on phase 1 and 2, 625 FTU/kg on phase 3, and 500 FTU/kg on phase 4 providing an estimated release of 0.13% STTD P in phase 1 and 2, 0.11% STTD P in phase 3, and 0.10% STTD P in phase 4.

[6] STTD P, standardized total tract digestible phosphorus.

Table 2.3. Chemical analysis of Exp. 1 diets (as fed-basis)[1]

	$MnSO_4$	Mn Hydroxychloride			
Calculated Mn, mg/kg	30	15	30	45	65
Analyzed Mn, mg/kg	46	32	41	57	65

[1]Values represent means from 20 composite samples (4 samples per treatment). For each treatment, samples were collected from multiple feeders, blended, subsampled, ground, and analyzed (Cumberland Valley Analytical Services, Waynesboro, PA).

Table 2.4. Chemical analysis of Exp. 2 diets (as fed-basis)[1]

	Mineral source[2]	
	Sulfate	Hydroxychloride
Calculated, mg/kg (added basis)		
Zn	110	110
Mn	16	16
Cu	150	150
Analyzed, mg/kg (total basis)		
Zn	211	220
Mn	30	36
Cu	168	151

[1] Values represent means from 8 composite samples (4 samples per treatment). For each treatment, samples were collected from multiple feeders from the two groups, blended, subsampled, ground, and analyzed (Cumberland Valley Analytical Services, Waynesboro, PA).

[2] Sulfate or hydroxychloride sources of Zn, Mn, and Cu were used for the 2 treatments.

Table 2.5. Effect of increasing Mn hydroxychloride on grow-finish pigs growth performance and carcass characteristics, Exp. 1[1]

	$MnSO_4$[2], mg/kg	Mn Hydroxychloride[3], mg/kg					*P* =[4]		
Item	30	15	30	45	65	SEM	Source	Linear	Quadratic
BW, kg									
d 0	39.9	39.9	39.9	39.9	39.9	1.22	0.988	0.977	0.994
d 43	80.0	79.9	80.4	80.1	80.4	2.78	0.839	0.828	0.984
d 113	133.0	133.3	133.3	132.2	133.4	3.86	0.832	0.857	0.671
d 0 to 43									
ADG, kg	0.93	0.93	0.93	0.93	0.94	0.042	0.949	0.468	0.940
ADFI, kg	2.11	2.13	2.13	2.08	2.16	0.091	0.627	0.693	0.207
G:F, g/kg	443	436	438	449	433	4.0	0.461	0.941	0.035
d 43 to 95									
ADG, kg	1.04	1.03	1.04	1.02	1.02	0.018	0.901	0.430	0.676
ADFI, kg	3.14	3.13	3.15	3.08	3.12	0.047	0.821	0.579	0.782
G:F, g/kg	332	329	330	332	328	9.0	0.598	0.883	0.359
d 0 to 95									
ADG, kg	0.99	0.98	0.99	0.98	0.98	0.013	0.930	0.876	0.689
ADFI, kg	2.66	2.66	2.67	2.61	2.67	0.068	0.753	0.874	0.467
G:F, g/kg	373	369	370	375	368	5.0	0.528	0.945	0.123
Individual pig weight CV, %[5]									
d 78	10.6	10.7	11.5	10.6	11.3	0.92	0.186	0.634	0.927

Carcass characteristics									
HCW, kg	98.9	99.4	98.9	97.6	99.0	2.60	0.985	0.566	0.283
Carcass yield, %	73.6	74.3	74.2	73.6	73.8	0.50	0.407	0.368	0.746
Backfat depth, mm[6]	17.8	18.1	18.0	17.8	17.9	0.97	0.551	0.424	0.706
Loin depth, mm[6]	64.7	65.1	65.1	65.8	65.4	1.28	0.514	0.411	0.654
Lean, %[6]	55.8	55.6	55.7	55.9	55.8	0.45	0.764	0.284	0.605
Mortality and removals, %	3.21	6.17	5.68	3.46	6.67	6.441	0.746	0.955	0.739

[1]A total of 2,025 pigs (initial BW of 39.9 ± 1.22 kg) were used in two groups with 27 pigs per pen and 15 replicates per treatment.

[2]Erachem, Veracruz, Mexico.

[3]IntelliBond M (IBM), Selko USA, Indianapolis, IN.

[4]Contrast coefficients were used to compare the effect of manganese sources at 30 mg/kg level and linear and quadratic effect within the increasing levels of IntelliBond M.

[5]At the first marketing event, a total of 1,937 pigs were weighted individually to calculate variation of final BW. Coefficient of variation of individual pig weight was calculated for each pen and analyzed to determine the effect of dietary treatment with pen as the experimental unit.

[6]Adjusted using HCW as covariate.

Table 2.6. Effect of sulfates and hydroxychloride mineral sources feed program on growth performance, weight distribution and carcass characteristics of grow-finish pigs, Exp. 2[1]

Item	Mineral source		SEM	*P* =
	Sulfates[2]	Hydroxychloride[3]		
BW, kg				
d 0	25.9	26.0	0.33	0.865
d 61	78.6	78.5	0.49	0.886
d 124	135.5	136.8	0.68	0.192
d 0 to 61				
ADG, kg	0.858	0.855	0.0044	0.656
ADFI, kg	1.98	2.01	0.0146	0.269
G:F, g/kg	433	427	2.3	0.050
d 61 to 124				
ADG, kg	0.935	0.960	0.0084	0.041
ADFI, kg	2.98	3.02	0.022	0.188
G:F, g/kg	314	318	2.6	0.295
d 0 to 124				
ADG, kg	0.895	0.906	0.0046	0.115
ADFI, kg	2.47	2.50	0.0161	0.203
G:F, g/kg	363	363	2.1	0.963
Individual pig weight CV, %[4]				
d 0	15.6	15.5	0.59	0.919
d 102	9.8	9.2	0.37	0.226
Carcass characteristics				
First marketing event				
HCW, kg	92.8	92.8	0.73	0.948
HCW CV, %	5.5	4.9	0.35	0.294
Carcass yield, %	73.1	73.3	0.27	0.655
Backfat depth, mm.[5]	16.18	16.09	0.312	0.842
Loin depth, mm.[5]	60.79	60.61	0.613	0.830
Lean, %[5]	56.3	56.4	0.22	0.818

Final marketing event				
HCW, kg	98.0	99.7	0.582	0.054
HCW CV, %	8.2	7.7	0.35	0.291
Carcass yield, %	72.1	72.4	0.26	0.467
Backfat depth, mm.[5]	15.68	16.07	0.202	0.176
Loin depth, mm.[5]	63.12	63.05	0.390	0.900
Lean, %[5]	56.9	56.7	0.14	0.208
Overall				
HCW, kg	96.7	97.8	0.55	0.189
HCW CV, %	7.5	6.9	0.28	0.170
Carcass yield, %	72.4	72.7	0.01	0.353
Backfat depth, mm.[5]	15.79	16.09	0.169	0.208
Loin depth, mm.[5]	62.52	62.41	0.302	0.809
Lean, %[5]	56.8	56.6	0.12	0.252
Total removals, %	3.7	5.3	0.99	0.226

[1] A total of 1,026 pigs (initial BW of 25.9 kg ± 0.33 kg) were used with 27 pigs per pen and 19 replicates per treatment. Treatments were assigned in a completely randomized design to compare the effect of sulfates and hydroxychloride (IntelliBond, Selko, Indianapolis, IN) sources on growth performance, weight distribution and carcass characteristics of grow-finish pigs.

[2] Cu, Mn, and Zn were provided by sulfate sources at 150, 16, and 110 mg/kg, respectively.

[3] Cu, Mn, and Zn were provided by hydroxychloride sources at 150, 16, and 110 mg/kg, respectively.

[4] Pigs were weighed individually to calculate variation of final BW. Coefficient of variation of individual pig weight was calculated for each pen and analyzed to determine the effect of dietary treatment with pen as the experimental unit.

[5] Adjusted using HCW as covariate.

Chapter 3 - Effects of finishing pig diets differing in Ca:P ratio, added phytase and 25(OH)D_3 on growth performance, serum 25(OH)D_3 and bone characteristics

Abstract

A total of 2,160 pigs (337 × 1050, PIC; initially 33.3 ± 1.43 kg) were used in a 114-d trial to determine the effects of feeding diets differing in Ca to P (Ca:P) ratio and vitamin D_3 source on growth performance and bone characteristics. Pigs were housed in mixed sex pens with 27 pigs per pen and 20 pens per treatment. The four treatments were assigned to pens in a randomized complete block design and consisted of: 1) a low phosphorus (LP) diet with STTD P at 80% of NRC requirement without added phytase and formulated to a 1.25:1 Ca:P ratio; 2) high phosphorus (HP) diet with STTD P at 115% of NRC (2012) requirement estimates without added phytase and formulated to a 1.25:1 Ca:P ratio; 3) HP with phytase (HP+phytase) diet with STTD P at 115% of NRC requirement considering 0.125% STTD P release from 600 FYT/kg HiPhorius (dsm-firmenich, Plainsboro, NJ) and formulated to 1.1:1 Ca:P ratio; and 4) Diet 3 except 25(OH)D_3 (Hy-D, dsm-firmenich, Plainsboro, NJ) replaced most of the supplemental vitamin D_3 (HP+25(OH)D_3). Diets were fed in 4 phases from 33 to 50, 50 to 75, 75 to 100, and 100 to 133 kg. Overall, the source of vitamin D_3 had no effect on growth performance. Pigs fed HP diets had improved ($P < 0.05$) ADG, ADFI, and G:F compared to those fed LP diets, and increased ADFI compared to those fed the HP+phytase diets. Pigs fed the HP diets had increased ($P < 0.05$) d 50 serum 25(OH)D_3 compared to pigs fed the LP diets and pigs fed the HP+25(OH)D_3 diets had increased ($P < 0.05$) serum 25(OH)D_3 compared to pigs fed the HP+phytase diets. For carcass characteristics, pigs fed the HP diets had greater ($P < 0.05$) HCW

and percentage lean than those fed LP diets. For bone analysis, pigs fed HP diets had greater ($P < 0.05$) bone ash (g) and breaking strength than pigs fed LP or HP+phytase diets. In conclusion, pigs fed LP diets had reduced growth performance and HCW. Dietary 25(OH)D_3 replacing vitamin D_3 did not affect performance but increased circulating 25(OH)D_3.

Introduction

Calcium and P are the most abundant minerals in the pig and play important roles in development and maintenance of the skeletal system, muscle deposition, and many other physiological functions (Crenshaw, 2001; NRC, 2012). Vier et al. (2019b) observed that daily gain and bone mineralization are maximized when phosphorus levels are 22% and 31%, respectively, greater than the NRC (2012) requirement estimate. The relationship of Ca and P is also important as demonstrated by a recent study by Vier et al. (2019a), who observed a quadratic response in ADG and final BW to Ca to P (Ca:P) ratio where they were maximized at a 1.25:1 Ca:P ratio. It was also demonstrated by González-Vega et al. (2016) that bone ash measured in femurs increased as the ratio increases when diets were adequate in P levels.

Vitamin D_3 has an important role in the absorption, metabolism, excretion, and reabsorption of Ca and P (Klein, 2012). The supplementation of vitamin D_3 in swine diets is necessary in modern production because pigs are housed indoors without adequate sunlight exposure necessary for vitamin D_3 synthesis (Norman, 1998). Vitamin D_3 can be supplemented using intermediate molecules of vitamin D_3 metabolism, such as 25-hydroxy-vitamin D_3 [25(OH)D_3]. Studies demonstrated that feeding 25(OH)D_3 increased serum levels (Sandoval et al., 2022; Williams et al., 2024) and improved bone mineralization (Zhang et al., 2022; Williams et al., 2024). However, there is no evidence for differences in growth performance have been observed in pigs when adequate levels of vitamin D_3 (NRC, 2012) were provided as vitamin D_3

or by 25(OH)D_3 and compared to diet that had additional 25(OH)D_3 on top a diet already containing adequate vitamin D_3 (O'Doherty et al., 2010; Duffy et al., 2018; Williams et al., 2024).

Phytase is an enzyme that when included in swine diets can release phytase bound P in digesta to make it more available for digestion and absorption (Humer et al., 2015). Added dietary phytase can also contribute to the release of other nutrients, such as trace minerals and amino acids, but its efficacy can be affected with high Ca:P ratios (Lei and Stahl, 2000). The addition of phytase in pig diets also reduces the inclusion of inorganic sources of phosphorus, which results in decreased diet costs and P excretion (Poulsen, 2000).

The objective of this study was to evaluate the effect of feeding finishing pigs diets differing Ca to P (Ca:P) ratio and vitamin D_3 source on growth performance, body weight variability, serum 25(OH)D_3, carcass characteristics, and bone characteristics. We hypothesized that feeding P levels below the NRC (2012) estimated requirement will reduce growth performance, carcass weight, and negatively affect bone characteristics. In addition, a higher Ca:P ratio will improve bone characteristics without affecting growth performance. Also, a partial replacement of vitamin D_3 with 25(OH)D_3 can provide benefits in bone characteristics of pigs fed well above the vitamin D_3 requirement estimate.

Materials and Methods

General

The Kansas State University Institutional Animal Care and Use Committee approved the protocol used in this experiment. The 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 totally slatted floors. Each pen (3.05 × 5.49 m^2)

provided approximately 0.62 m^2 per pig and was equipped with a 5-hole stainless steel dry self-feeder (Thorp Equipment, Thorp, WI) and a bowl waterer for *ad libitum* access to feed and water.

Animals and diets

Two groups of pigs (total 2,160 pigs; PIC 337 × 1050; initially 33.3 ± 1.43 kg) were used in a 114-d growth trial. Pigs were housed in mixed gender pens with 27 pigs per pen and 20 pens per treatment. The treatments were structured as a randomized complete block design and consisted of: 1) low phosphorus (LP) diet formulated to a 1.25:1 Ca:P ratio with STTD P at 80% of NRC requirement estimate without added phytase; 2) a high phosphorus (HP) diet formulated to a 1.25:1 Ca:P ratio with STTD P at 115% of NRC (2012) requirement estimate without added phytase; 3) HP with phytase (HP+phytase) diet formulated to a 1.1:1 Ca:P ratio with STTD P at 115% of NRC requirement estimate considering a 0.125% STTD P release from 600 FYT/kg phytase (HiPhorius, dsm-firmenich, Plainsboro, NJ); and 4) Diet 3 with 25(OH)D_3 (Hy-D, dsm-firmenich, Plainsboro, NJ) replacing a majority of the vitamin D_3 in the diet [HP+25(OH)D_3]. The first 3 treatment diets had 1,300 IU D_3/kg in the first three diet phases and 650 IU D_3/kg in phase four. The HP+25(OH)D_3 treatment had 1,000 IU of vitamin D_3 equivalency/kg from 25 µg/kg of 25(OH)D_3/kg + 300 IU vitamin D_3/kg in the first three phases and 500 IU vitamin D_3 equivalency/kg from 25(OH)D_3/kg + 150 IU vitamin D_3/kg in the fourth phase. All treatment diets were corn-soybean meal-based and manufactured at the New Horizon Farms Feed Mill in Pipestone, MN, and were formulated to meet or exceed NRC requirement estimates for growing-finishing pigs for their respective weight ranges (Table 1). Diets were fed in meal form with phase 1 fed from 33 to 50 kg, phase 2 from 50 to 75 kg, phase 3 from 75 to 100 kg, and phase 4 from 100 to 133 kg. Experimental diets were formulated with a premix containing Rovimix D_3

(dsm-firmenich) as the only source of vitamin D_3 for the LP, HP and HP+phytase treatments, whereas, for treatment HP+25(OH)D_3, a premix containing Rovimix Hy-D and Rovimix D_3 was used to supply the dietary vitamin D_3 requirements. Phytase was also added to the diet by hand-made premixes, which were added in place of corn.

Pigs were weighed approximately every 14 d to determine ADG, ADFI, and G:F. At the beginning of the study and on d 99, all the pigs were individually weighed to determine body weight variability. One mean BW pig per pen was identified with a tag on d 0 and blood samples were collected via jugular venipuncture on d 0, 50, and 99 from the same pig. Blood samples were centrifuged and serum was collected and analyzed for serum 25(OH)D_3 levels (Heartland Assays, Ames, IA). On d 99, the 3 heaviest pigs in each pen were selected and marketed, but carcass data was not collected. On the last day of the trial, final pen weights were obtained, and the pigs were tattooed with a pen identification number and transported to a U.S. Department of Agriculture-inspected packing plant (JBS Pork, Worthington, MN) for carcass data collection. Carcass measurements included HCW, loin depth, backfat depth, and percentage lean. The percentage lean calculations were obtained from a proprietary equation used by the packer. Carcass yield was calculated by dividing the pen average HCW by the pen average final live weight obtained at the farm. In addition, one pig per pen was used for bone collection from one front foot per pig. The third metacarpal was used for de-fatted bone ash evaluation following the procedures by Wensley et al. (2020) and the fourth metacarpal was used to determine bone breaking strength as described by Williams et al. (2024) at the Kansas State University Swine Laboratory.

Chemical analysis

Representative diet samples were collected from all the feeders of each treatment by phase and stored at -20°C until analysis. Samples of the diets were combined within the dietary treatment, and a composite sample per treatment was sent to a commercial laboratory (Midwest Laboratories, Omaha, NE) to analyze crude protein (990.03, AOAC International, 1990), ash (942.05, AOAC International, 1990), and Ca and P (985.01, AOAC International, 1990). In addition, two sub-samples for P and four sub-samples for Ca were analyzed in duplicates at the Soil Testing Lab from Kansas State University (Department of Agronomy, College of Agriculture, Manhattan, KS) using a nitric perchloric digestion technique. The results from the two laboratories were combined for the average dietary level of Ca and P.

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 (version 4.1.1 (2021-08-10), R Foundation for Statistical Computing, Vienna, Austria) with pen considered the experimental unit, and treatment as fixed effect. Contrast coefficients were used to evaluate the effects of P level in the diet (LP vs. HP), Ca:P ratio (HP vs. HP+phytase), and vitamin D_3 source (HP+phytase vs. HP+25(OH)D_3). Individual pig weight data on d 0 and 99 were used to calculate within-pen coefficient of variation which was analyzed in a similar manner to growth data. Hot carcass weight was used as a covariate for analysis of backfat depth, loin depth, and percentage lean. All results were considered significant at $P \leq 0.05$ and marginally significant between $P > 0.05$ and $P \leq 0.10$.

Results

General

The analyzed dietary Ca and P concentrations were consistent with calculated values used in diet formulation (Table 2). Overall, pigs were healthy and there were removals due to injury, health, or poor performance not related to dietary treatments (Table 3).

Growth performance and body weight variability

During the grower period (d 0 to 57), pigs fed the HP diet had increased ($P < 0.01$) ADG, ADFI, and G:F compared to those fed the LP diet (Table 3). Also, pigs fed the HP+phytase diet tended to have decreased ($P = 0.059$) ADFI compared to those fed the HP diet without phytase with no effect of vitamin D_3 source observed. In the finisher period (d 58 to 114), pigs fed the HP diet had increased ($P < 0.05$) ADG and ADFI compared to pigs fed the LP diet and ADFI tended to increase ($P = 0.083$) for pigs fed the HP diet compared to those fed the HP+phytase diet. Overall, pigs fed the HP diet had increased ($P < 0.05$) ADG, final BW, ADFI, and G:F compared to those fed the LP diet. No differences due to vitamin D_3 source was observed. Pigs fed the HP+phytase had decreased ($P = 0.020$) ADFI compared to those fed the HP diet, with no other differences observed in growth performance.

There was no evidence for difference ($P \geq 0.10$) in coefficient of variation in weight between the treatments on d 0 and 99 when individual weights were collected.

25(OH)D_3 serum levels

As expected, there were no differences on serum levels of 25(OH)D_3 between any of the treatments at d 0. On d 50, pigs fed the HP diet had increased ($P = 0.020$) serum 25(OH)D_3 compared to pigs fed the LP diets, and pigs fed the HP+25(OH)D_3 diets had increased ($P =$

0.001) serum 25(OH)D_3 compared to pigs fed the HP+phytase diets. Serum 25(OH)D_3 collected on d 99 did not show evidence of differences between treatments.

Carcass characteristics

Pigs fed the HP diet had greater ($P < 0.05$) HCW and lean percentage, with a tendency ($P = 0.092$) for reduced backfat depth compared to those fed the LP diet. There was a tendency to increase ($P = 0.054$) lean percentage and reduce ($P = 0.064$) backfat depth when the HP diet was fed compared to the HP+phytase diet.

Bones characteristics

Pigs fed the HP diet had greater ($P < 0.05$) bone ash weight and breaking strength than pigs fed the LP or HP+phytase diets. However, when bone ash is expressed as a percentage of bone composition, no evidence for treatment differences were observed ($P \geq 0.10$).

Discussion

Phosphorus plays a crucial role in bone and muscle development. Pettey et al. (2015) observed that 73 to 83% of retained phosphorus was found in the carcass (bones and muscle) during serial slaughter experiments in finishing pigs. This finding highlights the significant impact of P on the growth performance and carcass weight of pigs. Vier et al. (2019b) evaluated six STTD P levels ranging from 80% to 150% of the NRC (2012) estimated requirement utilizing pigs from 24 to 130 kg BW and, using a quadratic polynomial model, observed that ADG, G:F, and HCW were maximized when feeding STTD P at 122%, 116% and 130% of the NRC (2012) requirement estimate, respectively. In our study we evaluated dietary P levels at 80% and 115% of the NRC STTD P requirement estimate, and observed increased ADG, G:F and HCW when the high level of P was fed. The response observed was expected when comparing a diet deficient in P with one that it is at or over the estimated requirement (Cromwell

et al., 1970; Kühn and Männer, 2012). In the latest version of the NRC (2012), STTD P requirements were based on factorial estimates that account for P retention in the body, endogenous losses, urinary losses, marginal efficiency of using STTD P, and P requirements for maximum growth. Consequently, the genetic progress on lean tissue deposition made in modern genetics would require greater levels of P for bone and muscle deposition, which aligns with the results observed in our study and Vier et al. (2019b).

Pigs fed the HP diet had increased serum $25(OH)D_3$ on d 50 of the trial compared to those fed the LP diet. Serum $25(OH)D_3$ collected at d 99 did not show statistical differences, but were numerically higher for pigs fed the HP diet compared to the LP diet. The low levels of $25(OH)D_3$ detected at d 50 in pigs fed LP diets could be caused by lower levels of circulating P under the low dietary P scenario. When serum levels of P are low, the body will increase P absorption at the small intestine and renal reabsorption to conserve P and to minimize urinary P excretion. These regulatory steps are mediated by $1,25(OH)_2D_3$, the active form of vitamin D_3, which is converted to the active form from $25(OH)D_3$ in the kidney. Therefore, we expected to observe less $25(OH)D_3$ in circulation because it was converted to $1,25(OH)_2D_3$ to regulate the normal physiological mechanism when serum levels of P are low. Pigs were fed lower dietary concentrations of vitamin D_3 sources in phase 4. These lower concentrations likely resulted in the lack of treatment differences observed for serum $25(OH)D_3$ on d 99. The LP diet also decreased bone ash weight and breaking strength compared to the HP diet, which agrees with other authors' observations (González-Vega et al., 2016; Lagos et al., 2019; Williams et al., 2023).

Vitamin D_3 is essential for Ca and P absorption and is thus important for muscle growth and bone mineralization. Exposure to sunlight triggers synthesis of cholecalciferol (vitamin D_3),

beginning with converting the 7-dehydro-cholesterol (provitamin D_3) stored in the epidermis and dermis to pre-vitamin D_3. Pre-vitamin D_3 is then converted to vitamin D_3, which circulates in the blood and reaches the liver to be converted to 25(OH)D_3. This molecule is converted later in the kidney to 1,25$(OH)_2D_3$ (calcitriol), that will act in the target tissues (Norman, 1998). Due to the lack of sunlight exposure in modern swine housing facilities, dietary supplementation of vitamin D_3 is required. While vitamin D_3 is the most common source used to supplement swine diets in the United States (Faccin et al., 2023), incorporating 25(OH)D_3 into swine diets is considered to have a significant advantage over vitamin D_3 because, based on research in humans, it offers a high relative biological value, making the 25(OH)D_3 molecule more readily available (Cashman et al., 2012). According to the NRC (2012), the estimated D_3 requirement for pigs from 25 to 135 kg of BW is 150 IU/kg. In our study, from the 1,300 IU of vitamin D_3/kg supplemented, 1,000 IU of vitamin D3 equivalency was provided by 25(OH)D_3, equal to 25 μg/kg of 25(OH)D_3, meaning that pigs were fed at least 8 times their requirement estimate (NRC, 2012). While on d 50, pigs supplemented with 25(OH)D_3 as a partial replacement of vitamin D_3 had increased serum levels of 25(OH)D_3, at d 99, they were not statistically different but numerically 18.3% higher than pigs fed the diet containing equivalent levels of only vitamin D_3. The increased serum levels of 25(OH)D_3 has been observed in several studies (Duffy et al., 2018; Lütke-Dörhoff et al., 2022; Williams et al., 2024) where total vitamin D_3 levels were well above the NRC (2012) estimated requirement and 25(OH)D_3 was added in replacement to vitamin D_3 or added on top of a basal diet containing vitamin D_3 with no effects on growth performance or carcass criteria, similar to our results. However, Zhang et al. (2022) observed a quadratic improvement in final BW and ADG when supplementing 0, 25, 50, and 75 μg/kg of 25(OH)D_3 to a diet containing 25 μg/kg of vitamin D_3 (1,000 IU/kg of vitamin D_3) to pigs from 45 to 122

kg BW, with the maximum response of both traits observed at 50 μg/kg of 25(OH)D_3. These results are unique because most of the data published in pigs over 20 kg where 25(OH)D_3 was added on top of a diet containing vitamin D_3 at or over the NRC (2012) estimated requirement, similar to our study, did not show improvements in growth performance and carcass characteristics (Zhang et al., 2021; Sandoval et al., 2022; Williams et al., 2024). Similar to the results in our study, other authors did not observe differences in bone characteristics when adding 25(OH)D_3 in the diet on top or as a full replacement for vitamin D_3, even though the serum levels of 25(OH)D_3 were increased (O'Doherty et al., 2010; Regassa et al., 2015).

Calcium is necessary for skeletal growth, and it is stored in bones along with P in a 2.2:1 ratio to form hydroxyapatite crystals (Crenshaw, 2001). Parathyroid hormone and calcitonin work with vitamin D_3 in regulating the homeostasis of Ca and P stored in skeletal tissue. The Ca requirement has been established as the derivate of the appropriate ratio to STTD P for grow-finish pigs (NRC, 2102). This approach considers that Ca absorption depends not only on the daily intake of the pig but also on the Ca:P ratio (Crenshaw, 2001). In our study, 1.1:1 and 1.25:1 Ca:P ratios were compared by the HP+phytase and HP treatments, respectively. The HP+phytase diet was formulated to 1.1:1 Ca:P ratio and to contain 600 FYT/kg phytase which was considered to release 0.125% of STTD P creating the same STTD level in both treatments. The different Ca:P ratios used did not affect ADG or G:F but reduced ADFI was observed when the HP+phytase diet was fed. Based on these results, it seems that the P release assigned to the phytase source was accurate for growth. A reduction in ADFI was also observed by Vier et al. (2019a) when a lower Ca:P ratio was fed with the lowest intake when the Ca:P ratio was 0.75:1 compared to increasing ratios up to 1.25:1 Ca:P. The Ca:P ratio is essential for growth and bone mineralization because the level of one can affect the absorption of the other, but no difference

was observed in our results presumably because P levels were above the NRC (2012) estimates. This was demonstrated by Gonzalez-Vega et al. (2016) who evaluated Ca:P ratios between 0.30 to 2.90 at high and low STTD P levels in pigs from 25 to 50 kg of BW and observed that when P levels are at or above the pig's requirement, the range of Ca:P can be increased without affecting performance. The Ca:P ratio evaluated in our study did not affect serum levels of $25(OH)D_3$. Similar findings were reported in broilers (Zhang et al., 2020) but to our knowledge, no other studies have evaluated serum levels of $25(OH)D_3$ at different Ca:P ratios in pigs.

A tendency for decreased backfat depth and increase percentage lean was observed when feeding the HP diet without any effects on the other carcass traits. Williams et al. (2023) observed a tendency for a quadratic response on backfat when 0.90, 1.30, and 1.75 Ca:P ratios were fed, with the lowest backfat content at 1.30 Ca:P ratio. They also observed a linear reduction in HCW as the dietary Ca:P ratio increased. Our study did not observe this response; however, Vier et al. (2019a) fed five levels of Ca:P ranging from 0.75:1 to 2.00:1 and observed that HCW was maximized when feeding a 1.25:1 Ca:P ratio and decreased thereafter. In our study, pigs fed the HP+phytase diet had decreased bone ash (g/kg) and breaking strength but not bone ash on a percentage basis. Bone ash percentage refers to the proportion of the mineral content in bones, mostly Ca and P, after the organic material has been burned away. Breaking strength is a methodology used to assess the firmness or resistance of the bone tissue, and is highly correlated with ash content (Nielsen et al., 2007). It was as previously mentioned, the P release value assigned to the phytase used in the HP+phytase diet appeared to be accurate based on the growth performance results, but the reduction in bone ash (g/kg) and breaking strength suggests that the release value was overestimated for these response criteria. Vier et al. (2019a) evaluated ash on a percentage basis and observed a linear increase in bone ash percentage as the

Ca:P increased. Conversely, bone ash percentage was not influenced by Ca:P ratio in our study, likely because the range in ratios was not great enough to initiate a change in bone ash percentage.

Finally, BW variability was evaluated at d 0 and 99 by individually weighing each pig and calculating pen CV. No treatment effects were observed for BW variability. Tolosa et al. (2021) observed that a pig cohort population has an inherent BW coefficient of variation of approximately 20% and 10% at 1.35 and 130 kg BW, respectively. Our BW variability at marketing ranged from 9.3 to 9.6, thus similar to Tolosa et al. (2021) estimates, indicating no effects of the treatments used.

Conclusion

In summary, the present data show that feeding deficient P levels reduced growth performance, HCW, and bone characteristics compared to feeding P greater than the NRC (2012) requirement estimate. The partial replacement of vitamin D_3 with 25(OH)D_3 increased serum 25(OH)D_3 levels as expected, but no differences in growth or bone characteristics were observed. The HP+phytase diet, reduced feed intake, bone ash weight, and bone breaking strength compared to the HP diet. This could suggest that the phytase release value assigned could have been overestimated based on the bone responses observed.

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Table 3.1. Composition of experimental phases 1 to 4 diets (as-fed basis)[1]

	Phase 1		Phase 2		Phase 3		Phase 4	
Item	LP/HP[2]	HP+phytase /25(OH)D_3[3]	LP/HP[2]	HP+phytase /25(OH)D_3[3]	LP/HP[2]	HP+phytase /25(OH)D_3[3]	LP/HP[2]	HP+phytase /25(OH)D_3[3]
Ingredients, %								
Corn	66.01	67.22	73.32	73.64	78.82	79.12	81.46	81.79
Soybean meal, 46.5% CP	28.78	28.76	22.65	22.62	17.33	17.30	14.86	14.80
Choice white grease	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
Limestone	[2]	0.93	[2]	0.87	[2]	0.83	[2]	0.80
Monocalcium P, 21% P	[2]	0.40	[2]	0.22	[2]	0.13	[2]	---
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
L-Lys-HCl	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
DL-Met	0.09	0.09	0.06	0.06	0.03	0.03	0.02	0.02
L-Trp	---	---	0.01	0.01	0.01	0.01	0.02	0.02
Thr[4]	0.12	0.12	0.11	0.11	0.11	0.11	0.12	0.18
L-Val	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01
Tribasic copper chloride	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Vitamin-trace mineral premix[5]	0.15	0.15	0.15	0.15	0.15	0.15	0.08	0.08
Phytase[6]	---	0.10	---	0.10	---	0.10	---	0.10
TOTAL	100	100	100	100	100	100	100	100

Calculated analysis

Standardized ileal digestible (SID) amino acids, %								
Lys	1.12	1.12	0.97	0.97	0.84	0.84	0.78	0.78
Ile:Lys	63	63	62	62	61	61	60	60
Leu:Lys	132	132	138	138	144	144	148	148
Met:Lys	32	32	31	31	29	29	29	29
Met and Cys:Lys	56	56	56	56	56	56	56	56
Thr:Lys	62	62	62	62	63	63	65	71
Trp:Lys	18.3	18.3	18.2	18.2	18.1	18.1	18.3	18.3
Val:Lys	70	70	70	70	70	70	70	70
His:Lys	42	42	42	42	42	43	43	43
Total Lys, %	1.26	1.26	1.09	1.09	0.95	0.95	0.88	0.88
NE, kcal/kg	2,516	2,523	2,555	2,565	2,589	2,599	2,609	2,620
SID Lys:NE, g/Mcal	4.45	4.44	3.80	3.78	3.24	3.23	2.99	2.98
CP, %	19.6	19.7	17.3	17.3	15.1	15.2	14.2	14.2
Ca, %	[2]	0.51	[2]	0.44	[2]	0.39	[2]	0.35
STTD P, %	[2]	0.36	[2]	0.31	[2]	0.28	[2]	0.25

[1] Phases 1 to 4 were fed from approximately 33 to 50, 50 to 75, 75 to 100, and 100 to 133 kg, respectively.

[2] LP and HP phase treatment diets were combined in this column. For phase 1, LP diet = 1.14% limestone and 0.48% monocalcium P (21% P) to provide a total content of 0.60% Ca and 0.25 STTD P % in the diet and HP diet = 1.28% limestone and 1.06% monocalcium P (21% P) to provide a total content of 0.76% Ca and 0.36 STTD P % in the diet. For phase 2, LP diet = 1.08% limestone and 0.41% monocalcium P (21% P) to provide a total content of 0.55% Ca and 0.22 STTD P % in the diet and HP diet = 1.19% limestone and 0.88% monocalcium P (21% P) to provide a total content of 0.68% Ca and 0.31 STTD P % in the diet. For phase 3, LP diet = 1.02% limestone and 0.32% monocalcium P

(21% P) to provide a total content of 0.50% Ca and 0.19 STTD P % in the diet and HP diet = 1.13% limestone and 0.79% monocalcium P (21% P) to provide a total content of 0.62% Ca and 0.28 STTD P % in the diet. For phase 4, LP diet = 0.99% limestone and 0.24% monocalcium P (21% P) to provide a total content of 0.46% Ca and 0.17 STTD P % in the diet and HP diet = 1.07% limestone and 0.61% monocalcium P (21% P) to provide a total content of 0.56% Ca and 0.24 STTD P % in the diet. In both treatments at phase 4, vitamin D_3 was at 650 IU/kg.

[3] HP+phytase and HP+25(OH)D_3 diets were combined in this column. HP+phytase diet contained 1,300 IU/kg of D_3 and HP+25(OH)D_3 contained 1,000 IU/kg of 25(OH)D_3 and 300 IU/kg of D_3 in phases 1 to 3. In phase 4, HP+phytase diet contained 650 IU/kg of D_3 and HP+25(OH)D_3 contained 500 IU/kg of 25(OH)D_3 and 150 IU/kg of D_3.

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

[5] Vitamin and trace mineral premix containing Rovimix D_3 (dsm-firmenich; Plainsboro, NJ) as the only source of vitamin D_3 for the HP, LP and HP+phytase treatments; whereas, for treatment HP+25(OH)D_3 a premix containing Rovimix Hy-D and Rovimix D_3 was used to meet vitamin D_3 requirements.

[6] HiPhorius (dsm-firmenich; Plainsboro, NJ) was added in a blend of 0.011 kg of the product and 0.896 kg of ground corn to achieve 600 FYT/kg, providing an estimated release of 0.125% STTD P for treatments containing phytase.

Table 3.2. Total calcium and phosphorus analysis of the diets (as-fed basis)[1]

Item	LP	HP	HP+phytase	HP+25(OH)D_3
Total Ca, %[2]				
Calculated				
Phase 1	0.60	0.76	0.51	0.51
Phase 2	0.55	0.68	0.44	0.44
Phase 3	0.50	0.62	0.39	0.39
Phase 4	0.46	0.56	0.35	0.35
Analyzed				
Phase 1	0.60	0.75	0.51	0.45
Phase 2	0.52	0.71	0.51	0.45
Phase 3	0.53	0.62	0.39	0.52
Phase 4	0.44	0.58	0.42	0.42
Total P, %[2]				
Calculated				
Phase 1	0.48	0.61	0.47	0.47
Phase 2	0.44	0.54	0.40	0.40
Phase 3	0.40	0.50	0.36	0.36
Phase 4	0.37	0.45	0.32	0.32
Analyzed				
Phase 1	0.48	0.61	0.47	0.47
Phase 2	0.42	0.48	0.35	0.33
Phase 3	0.38	0.47	0.34	0.34
Phase 4	0.32	0.39	0.24	0.25

[1] Values represent means from 8 composite samples (4 samples per treatment). For each treatment, samples were collected from multiple feeders from the two groups, blended, subsampled, ground, and analyzed (Midwest Laboratories, Omaha, NE; Soil Testing Lab, Department of Agronomy, College of Agriculture, Kansas State University, Manhattan, KS).

[2] Values represent the average of nine and five replicated analysis for each sample of Ca and P, respectively, at both laboratories.

Table 3.3. Effects of feeding finishing pig diets differing in Ca:P ratio and vitamin D_3 source on growth performance, body weight variability, serum 25(OH)D_3, carcass characteristics, and bone characteristics[1]

	Treatments							
	LP[2]	HP[3]	HP+phytase[4]	HP+25(OH)D_3[5]				
STTD P:	80% NRC	115% NRC	115% NRC	115% NRC				
Ca:P:	1.25:1	1.25:1	1.1:1	1.1:1				
Phytase, FYT/kg:	0	0	600	600		P=[6]		
Item Vitamin D_3, IU/kg:	1,300	1,300	1,300	300 + 1,000 IU from 25(OH)D_3	SEM	P level	Vit. D	Ca:P
BW, kg								
d 0	33.3	33.2	33.2	33.2	1.43	0.911	0.911	0.937
d 114	129.6	133.5	132.5	132.0	1.98	0.008	0.697	0.497
Grower period, d 0-57								
ADG, kg	0.84	0.88	0.87	0.87	0.010	<0.001	0.660	0.349
ADFI, kg	2.04	2.11	2.07	2.05	0.040	0.001	0.199	0.059
G:F, g/kg	410	418	422	426	5.0	0.010	0.263	0.228
Finisher period, d 58-114								
ADG, kg	0.88	0.91	0.90	0.89	0.021	0.038	0.658	0.506
ADFI, kg	2.63	2.72	2.66	2.63	0.039	0.016	0.441	0.083
G:F, g/kg	332	336	339	339	4.8	0.368	0.916	0.510
Overall, d 0-114								
ADG, kg	0.86	0.90	0.89	0.88	0.008	<0.001	0.526	0.264

ADFI, kg	2.33	2.40	2.35	2.33	0.031	<0.001	0.177	0.020
G:F, g/kg	368	374	377	376	3.8	0.027	0.434	0.194
CV, %[7]								
d 0	15.4	15.1	15.4	14.6	0.50	0.647	0.256	0.652
d 99	9.3	9.4	9.6	9.5	0.31	0.814	0.723	0.676
25(OH)D_3, ng/ml[8]								
d 0	22.2	23.8	23.8	23.3	1.32	0.368	0.756	0.996
d 50	50.2	61.1	53.9	70.2	3.43	0.020	0.001	0.123
d 99	48.4	54.5	55.1	65.2	4.48	0.331	0.109	0.926
Carcass characteristics								
HCW, kg	94.8	97.5	97.0	97.3	0.89	0.001	0.709	0.551
Yield, %	72.8	73.0	73.1	73.0	0.37	0.630	0.815	0.807
Backfat depth, mm.[9]	16.3	15.8	16.4	16.4	0.22	0.092	0.961	0.064
Loin depth, mm.[9]	64.8	65.5	65.1	65.7	0.73	0.127	0.264	0.363
Lean, %[9]	56.7	57.1	56.7	56.8	0.15	0.044	0.502	0.054
Total removals, %	7.0	6.7	6.7	8.5	1.36	0.624	0.624	0.624
Bone analysis[10]								
Bone ash, g	8.47	9.99	8.97	9.22	0.219	<0.001	0.396	<0.001
Bone ash, %	58.3	58.9	58.9	59.7	0.96	0.558	0.422	0.994
Breaking strength, kg[11]	228	289	243	250	12.0	< 0.001	0.668	0.004

[1] A total of 2,160 pigs (initial BW of 33.3 kg ± 1.43 kg) were used in two groups with 27 pigs per pen and 20 replicates per treatment.

[2] Low phosphorus diet (LP) contained 1,300 IU vitamin D_3/kg in phases1-3 and 650 IU in phase 4, 1.25:1 Ca:P ratio with STTD P at 80% of NRC 2012 requirement (0.25%, 0.22%, 0.19%, and 0.17% in phase 1, phase 2, phase 3, and phase 4, respectively) without phytase.

[3] High phosphorus diet (HP) contained 1,300 IU vitamin D_3/kg in phases 1-3 and 650 IU in phase four, 1.25:1 Ca:P ratio with STTD P at 115% of NRC 2012 requirement (0.36%, 0.31%, 0.28%, and 0.24% STTD P in phase 1, phase 2, phase 3, and phase 4, respectively) without phytase.

[4] High phosphorus diet with phytase (HP+phytase) contained 1,300 IU vitamin D_3/kg diet in phases 1-3 and 650 IU in phase four, 1.1:1 Ca:P ratio with STTD P at 115% of NRC 2012 requirement (0.36%, 0.31%, 0.28%, and 0.24% STTD P in phase 1, phase 2, phase 3, and phase 4, respectively) considering 0.125% STTD P from 600 FYT/kg HiPhorius.

[5] High phosphorus diet with 25(OH)D_3 (HP+25(OH)D_3) contained 1,000 IU 25(OH)D_3 + 300 IU vitamin D_3/kg diet in phases 1-3and 500 IU 25(OH)D_3 + 150 vitamin D_3 in phase 4, 1.1:1 Ca:P ratio with STTD P at 115% NRC 2012 requirement (0.36%, 0.31%, 0.28%, and 0.24% STTD P in phase 1, phase 2, phase 3, and phase 4, respectively) considering 0.125% STTD P from 600 FYT/kg HiPhorius.

[6] Contrast coefficients were used to compare the effect of STTD P level (LP vs. HP), vitamin D_3 source (HP+phytase vs. HP+25(OH)D_3), and Ca:P (HP vs. HP+phytase).

[7] Pigs were weighed individually to calculate BW variability.

[8] A sample of blood was taken from 1 pig per pen at three different times during the trial by jugular venipuncture.

[9] Adjusted using HCW as covariate.

[10] One pig per pen (20 pens per treatment) was sent to JBS packing plant (Worthington, MN) and the right 3rd metacarpal was collected to determine bone ash weight and percentage bone ash, and the right 4th metacarpal was collected to determine breaking strength.

[11] Bone breaking strength is reported as the maximum compressive load on each bone with an Instron (Instron 5569, NV Lab, Norwood, MA).

Chapter 4 - Modeling grow-finish pig growth performance and carcass responses to dietary net energy using ingredients nutrient values from four different databases

Abstract

Data from 94 grow-finish pig trials with diets differing in net energy (NE) and other nutrients were used in a meta-analysis to model growth performance and carcass characteristics based on the diet's NE, CP, standardized ileal digestible (SID) Lys, NDF, and lysine to NE (Lys:NE) ratio. Energy and nutrient concentrations in all diets were determined using values from four different databases (NRC, 2012 [NRC]; CVB, 2022 [CVB]; INRA, 2024 [INRA]; Rostagno et al., 2024 [BR]). Stepwise selection using Akaike information criteria was used for model selection considering the linear, quadratic, and interactive effects of NE, SID Lys, CP, NDF, Lys:NE ratio, and BW. Model variable predictors were generated using a linear mixed model. Selected models indicated that ADG and G:F increase as dietary NE increases in the four databases evaluated. However, the magnitude of response in G:F differed between ingredient databases at the early and late stages of the finishing period. The model using BR database appears to overestimate ADG when using high NDF concentrations. Models generated for all 4 databases predicted greater changes in ADG and G:F when the Lys:NE ratio was maintained compared to when a constant SID Lys level was used. Dressing percentage (DP), backfat depth (BF), and loin depth (LD) increased and percentage lean (PL) decreased as NE increased with different magnitudes of response depending on the database. However, when a constant Lys:NE ratio was not maintained, increasing NE did not change DP predictions using the BR database, with the NRC and INRA models predicting a slight increase only at high NE levels. The CVB model suggested

a similar response in DP whether Lys:NE ratio was maintained or not. For all the ingredient databases, BF and PL were predicted to linearly increase and decrease, respectively, as NE increased whether the Lys:NE ratio was maintained or not, but the changes were greater without maintaining the Lys:NE ratio. The models predicted LD to increase quadratically, with a greater response at low NE levels and the response plateauing at high dietary NE, regardless of whether the Lys to NE was maintained or not. In conclusion, the models generated provide estimates of the magnitude of the change for growth and carcass parameters of grow-finish pigs when dietary NE and other nutrients changed, with the magnitude of the changes being greater when Lys:NE ratio are maintained compared to constant levels of Lys.

Introduction

The grow-finish period (25 to 135 kg) accounts for more than 70% of the total feed a pig consumes, with energy being the largest cost in swine diets. Other dietary nutrients are set based on their ratio to energy content of the diet (Chiba et al., 1991). Therefore, the energy concentration of the diet will determine other nutrient profiles and impact growth performance and feed cost.

Nitikanchana et al. (2015) developed a regression model based on published articles from 1991 to 2012, in which energy levels were evaluated in pig diets from 25 to 130 kg on growth performance. The resulting regression equations predicted average daily gain (ADG) and gain-to-feed ratio (G:F) using dietary net energy (NE), ether extract (EE), and BW as inputs. The regression analysis showed improvements in growth performance as NE levels increased, indicating that NE is an important predictor variable of growth performance; however, a validation experiment determined that the estimations were not accurate when diets contained high fiber content (Nitikanchana et al., 2015).

Noblet et al. (1994) published NE prediction equations for growing pigs based on digestible nutrient contents, DE, ME, and chemical characteristics. These equations were adopted by the Institut National de la Recherche Agronomique (INRA) using ME intake, energy retention, and total heat production through indirect calorimetry of pigs. The NRC (2012) used these equations to assess NE for most feed ingredients, but for vegetable oil and animal fat sources, the comparative slaughter approach was employed. The Dutch feed tables (CVB) also used Noblet et al. (1994) equations, but with digestible nutrients. The Brazilian tables ([BR], Rostagno et al., 2024) applied these equations using their own ME values from total fecal collection in pigs to determine NE. Consequently, there are differences in nutrient values between databases. These four databases serve as the major reference values used by swine nutritionists in diet formulation.

The objective of this meta-analysis was to develop regression equations to predict growth performance and carcass characteristics of growing-finishing pigs based on dietary NE and other nutrient values, using published data from 1991 to 2024. A second part of this objective was to develop the equations utilizing the nutrient composition of feed ingredients from NRC, CVB, ([CVB];2022), INRA ([INRA];2024), and Rostagno et al.([BR];2024) databases. We hypothesize that developing a regression model to predict growth performance and carcass characteristics of pigs from 20 to 130 kg of BW, with studies including current genetics, modern diets with more co-product ingredients providing more fiber, as well as corn-SBM-based diets with or without the addition of animal fat or vegetable oil, will help to improve the robustness and predictions of growth performance and carcass parameters in swine formulation. Our second hypothesis was that the predictions would change when regression equations are developed using the nutrient content from different ingredient databases.

Materials and Methods

A literature search was conducted utilizing the Academic Search Premier, CAB Direct, and Web of Science search engines with the keywords “energy AND growth AND pig(s)”, “fiber AND growth AND pig(s)”, or “fat AND growth AND pig(s). The data generated was derived from refereed and nonrefereed publications, including journal publications, thesis, and technical memos. The search was limited to research studies published from 1991 to 2024. Publications had to be research conducted on growing-finishing pigs (approximately 20 to 130 kg BW), provide growth performance data, and feed ingredients and their inclusion rates in each dietary treatment had to be reported to recreate the diets. The initial search yielded 127 trials.

Selection for inclusion and exclusion criteria

The initial search was then evaluated for the following criteria: treatment diets had to vary in NE after diets were reformulated, pigs had to be provided ad libitum access to feed and water, pigs could not be individually housed, treatments had to be replicated (≥ 4 replications per treatment), and the experimental design had to include randomization (completely randomized design or randomized complete block design). Trials using entire males, immunocastrated pigs, pure-bred genetics, and ractopamine HCl were excluded. Studies that had treatments where certain feed ingredients were withdrawn for part of the study were excluded but the treatments without withdrawal were included. A total of 33 experiments were excluded for reason of: individually housed pigs (6), less than four replications (1), entire males and/or immunocastrated pigs (3), pigs over 130 kg BW (1), ingredient composition was not available or diet composition were not able to be recreated (9), ractopamine HCl was used (2), growth performance was reported only as overall period without data by phase (8), the design was to measure residual feed intake (1), pure-bred genetics were used (1), and energy was not changed among diets after

re-formulation (1). The final database included 94 experiments from 74 publications with a total of 52,663 pigs, where 74 experiments reported growth performance results, and 67 experiments reported carcass information (Table 1).

Diet reformulation

Diets for each experimental treatment within trial were reformulated in Microsoft Excel-based formulator using the NRC, CVB, INRA, and BR nutrient loading values for ingredients to standardize ingredient nutrient concentrations and compare the model output between the different nutrient databases. The nutrient values used were NE (Mcal/kg), standardized ileal digestible lysine (SID Lys [%]), crude protein (CP [%]), and neutral detergent fiber (NDF [%]) on an as-fed basis. The Lys to calorie ratio (Lys:NE [g/Mcal]) was calculated and used as predictor variable. For plant-based ingredients that did not report energy content, it was estimated as a ratio of the corn energy value. The average energy corn ratio from the databases that reported the energy of the missing value was used for the energy system without a reported value. For example, the BR ingredient library did not have a NE value for field peas. The NE of field peas as a ratio to the NE of corn calculated from the reported values in the NRC, CVB, and INRA were 91%, 91%, and 89%, respectively. The average (90%) of those three values was multiplied by the NE of corn from the BR database to estimate a NE value for field peas to use in the BR models. The same approach was used to estimate the missing values of fats and oils, using the average ratio relative to the NE of soybean oil (SBO). For ingredients missing SID Lys, CP, and NDF values, the average values reported by the other ingredient databases were used. The nutrient content of synthetic amino acids that were not reported in the four sources was taken from supplier datasheets. The ingredients missing at least one of the values for each system were the following: camelina cake, corn starch, glycerol, oat hulls, olive cake, rice hulls, wheat

gluten feed, and wheat straw for NRC; animal-vegetable blend, camelina cake, corn bran, corn grits, Nutridense corn, cottonseed oil, faba beans, glycerol, high protein corn dried distiller grains with solubles (HPDDGS), olive cake, sorghum dried distiller grains with solubles (SDDGS), and wheat straw for CVB; animal-vegetable blend, canola meal, coconut oil, corn HPDDGS, Nutridense corn, corn oil, cottonseed oil, flax seed oil, glycerol, olive oil, safflower oil, and sorghum DDGS for INRA; and animal-vegetable blend, camelina cake, canola meal, coconut oil, copra meal, corn bran, corn grits, Nutridense corn, cottonseed oil, faba beans, field peas, fish oil, flax seed oil, lentils, oat hulls, olive cake, olive oil, palm kernel meal, rice hulls, safflower oil, sorghum DDGS, sunflower meal, wheat DDGS, wheat gluten feed, and wheat straw for BR.

Database preparation

All selected trials were included in a database with an individual experiment number with the corresponding growth performance, carcass data, and nutrient composition of the diet. Reported data included initial and final BW, ADG (g), average daily feed intake (ADFI [g]), and G:F (g/kg) for each feeding period. For papers that reported feed efficiency as feed to gain ratio (F/G), an inverse proportion was calculated using ADG and ADFI values. Average BW was calculated for each treatment by averaging the initial and final BW of each period. If days on feed were not reported for each period, they were calculated by dividing average BW and ADG. Hot carcass weight (HCW), dressing percentage (DP), backfat depth (BF), loin depth (LD), and percentage lean (PL) were also recorded. The nutrient composition of the diet for carcass evaluation was calculated as weighted average of nutrient composition of the diets fed and days on each phase during the finisher period. Measurements of mean variability were collected for each of the response criteria. The main measurement reported was SEM and it was used as a

weighting factor for statistical analysis. For those studies that reported SD or CV, SEM were calculated from the data.

Statistical analysis

Regression equations were developed with a lmer model from lme4 package of R Studio (Version 4.1.1, R Core Team. Vienna, Austria) to predict ADG, G:F, HCW, DP, BF, LD, and PL depending on the following predictor variables: NE, SID Lys, CP, NDF, Lys:NE ratio, and BW. The dietary NE applied within each experiment and phase was the observational and experimental unit, and experiment was included in the model as a random effect. The inverse of the reported SEM was utilized with the WEIGHT statement to account for heterogeneous errors across studies. Linear and quadratic terms of the predictor variables were made available to the model and eligible for selection, as well as interactive terms between linear predictor variables. A backward stepwise selection methodology was used to select the best predictor variables for each response based on the Akaike information criteria (AIC) where the model that minimized AIC was selected as the preferred candidate model for each response criteria. Residual analysis was conducted for all the models obtained to visually assess statistical assumptions which were reasonably met.

Regression model predictions

Using the prediction equations developed for each of the four ingredient databases in this meta-analysis, a tool was developed in Microsoft Excel to visualize and quantify the model predictions. The tool allows the user to predict the responses by BW ranges at different levels of the dietary components. To standardize the comparison of predicted responses to dietary NE across databases and recognizing the inherent relationship between predictor variables as NE changes, equations were used to adjust SID Lys, CP, and NDF as dietary NE changed to achieve

realistic predictions. The SID Lys value was calculated from the Lys:NE ratio at each BW using the predicted equation from Menegat et al. (2019). The estimated SID Lys and total nitrogen requirements for pigs from 25 to 135 kg (NRC, 2012) were regressed to obtain the estimated CP level by converting total nitrogen to CP using the 6.25 multiplication factor. The NDF content used was regressed based on the content of NE and NDF of the experimental diets used in this meta-analysis for each ingredient database. The outputs from the equations obtain with this tool were used in the results and discussion section to explain the prediction of each response. The following input ranges for growth performance responses should be used in the prediction equations for the most accurate estimations: 40 to 125 kg BW, 2.20-2.80 Mcal NE/kg, 0.50 to 1.20% SID Lys, 10.4 to 19.0% CP, 7.9 to 19.8% NDF, and 2.20 to 5.20 Lys:NE ratio. While the models can predict outside these boundaries, the likelihood of obtaining unrealistic outputs increases.

Regression equations for HCW predictions were not estimated. Many experiments reported values where pigs were fed to a common final BW and not to the same days on feed. Thus, the HCW was more related to days on feed than dietary components.

Results and Discussion

Growth performance predictions

The final models for ADG and G:F included 691 observations from 74 experiments. The database included experiments with pigs from 17 to 140 kg with diets ranging from 1.98 to 3.05 Mcal/kg, 0.24 to 1.34% SID Lys, 8.4 to 25.7% CP, 6.9 to 28.7% NDF, and 0.94 to 5.68 SID Lys:NE.

Average daily gain

For all four ingredient databases evaluated, the regression equation for ADG with the lowest AIC included linear, quadratic, and interactive terms of NE, SID Lys, CP, NDF, Lys:NE, and BW (Table 2). The selected models predicted increased ADG as dietary NE increased. However, the magnitude of the response was different between ingredient databases for each additional Mcal of NE (Figure 1).

Nitikanchana et al. (2015) developed a similar model using the NRC database, but only included the linear term of NE and linear and quadratic terms of BW. They predicted an improvement of 11.35 g in ADG for every 100 kcal/kg of NE added into the diet which is lower than our predictions from the same NRC database. Our model predictions using the NRC database included NE and other nutrients as inputs, therefore the predicted changes in ADG as NE increases is also influenced by the other changes that occur in diet formulation as NE changes. The predicted improvements in ADG with changes in NE are greater than Nitikanchana et al. (2015), however, the magnitude of the improvement depends on the BW and starting NE level. The predictions from the NRC, CVB, and INRA ingredient databases showed that the magnitude of the ADG response increases as NE increases, and is dependent on phase of production, being greater at early stages of the finishing period than at later finisher for the NRC database, whereas for the predictions from the CVB and INRA ingredient databases are greater at late finisher than at early finisher (Figure 1). The NRC database predictions agree with improvements in growth rate observed by Bromm et al. (2023) from 28 to 90 kg, when pigs are in an energy-dependent phase of growth where daily energy intake is limited by intake capacity. The predictions utilizing the BR database were different. The magnitude of the ADG response in response to increasing energy was greater at the early finisher than at late finisher at low NE

levels but greater in the late finishing period than the early period at high NE levels. The reduction in the magnitude of the ADG response to increasing energy observed at low NE levels in the late finisher is related to the NDF content of the ingredients reported by BR. The NDF reported values by BR includes the ash content of the ingredients, resulting in a higher value of NDF for each ingredient and influencing some ingredients more than others. As a result, the magnitude of the ADG response decreased at low NE levels in the late finisher period compared to the other databases.

The equations obtained with our meta-analysis included linear, quadratic, and interactive terms of NE and other dietary components; therefore, the predicted ADG cannot be estimated from a change in NE alone. This should not be surprising because changing the NE content of the diet usually results in changes in many other diet components including NDF and CP. The response to diet NE also depends on whether SID Lys and other amino acids are maintained as a ratio to energy (Chiba et al., 1991; Marçal et al., 2019). Results from this meta-analysis show a similar response with the four models predicting a greater increase in ADG as NE is increased when Lys:NE ratio was maintained as compared to when the ratio was not maintained and SID Lys remained constant as NE increased (Figure 2).

Gain:feed ratio

Similar to ADG, the regression equations developed to predict the G:F response included linear, quadratic, and interactive terms of NE, SID Lys, CP, NDF, Lys:NE ratio, and BW (Table 3). The selected models indicated that G:F increased as dietary NE increased for the four ingredient databases. The magnitude of the predicted G:F responses to energy were lower at low NE levels than at high NE levels for the CVB, INRA, and BR ingredient databases. Conversely, the magnitude of the G:F predicted responses to changing NE using the NRC database was

similar as NE increased for all weight ranges except for the late finisher where the predicted response increased as dietary NE increased (Figure 3). The differences in the magnitude of the G:F response is related to the type of ingredients used at different levels of NE. Diets with low NE levels typically contain ingredients with high NDF content which has been demonstrated to reduce G:F during the finisher period compared to diets containing higher NE levels and reduced levels of NDF (Graham et al., 2014; Nitikanchana et al., 2015; Royall et al., 2024). In contrast, increasing NE concentrations are often achieved through the addition of animal fat or vegetable oil which consistently increases G:F in the finisher period (Friesen et al., 1991; Liu et al., 2018; Bromm et al., 2023). Nitikanchana et al. (2015) also observed linear improvements in G:F as NE increased, but the magnitude of the G:F response was constant for each additional Mcal of NE. This is a result of Nitikanchana et al. (2015) model including only linear terms of NE, BW, and fat content as predictor variables, whereas our model contained linear, quadratic, and interactive terms utilizing more dietary components as predictors.

At different magnitudes, the four models developed in our meta-analysis predicted an increase in G:F as NE increased when Lys:NE ratios were maintained (Figure 4). Predictions from the INRA model are slightly higher compared to the other three ingredient databases. The results could be attributed to a lower NE content of the diets when using nutrient values from INRA compared to the other databases. Therefore, the G:F predictions at the same NE level included certain types of diets and/or ingredients with the INRA database that are different compared to the other three databases, resulted in higher predictions. The predictions showed less improvement in G:F when SID Lys remained constant as a percentage of the diet as compared to when a constant Lys:NE ratio was maintained. Marçal et al. (2019) evaluated increase NE levels by adding fat in the diet, with and without adjusting the SID Lys level of the

diet. They observed improvements on G:F as NE increased even when SID Lys was not maintained as a ratio to NE content; however, the magnitude of response was less than when SID Lys:NE was maintained. Therefore, the four databases seem to provide an accurate estimate of how G:F responds to changes in diet composition with and without maintaining the Lys:NE ratio.

Carcass characteristics

The final models for DP, BF, LD, and PL included 244, 244, 220, and 142 observations, respectively, from 67 experiments. The databases included experiments with pig final BW from 55 to 140 kg and diets ranging from 2.01 to 2.85 Mcal/kg, 0.38 to 1.02% SID Lys, 8.4 to 24.0% CP, 6.7 to 30.9% NDF, and 1.46 to 4.41 SID Lys:NE. The regression equation included linear, quadratic, and interactive terms of NE, SID Lys, CP, NDF, Lys:NE ratio, and BW (Tables 4, 5, 6, and 7).

Dressing percentage

For the four ingredient databases evaluated, the regression equation for DP with the lowest AIC included linear, quadratic, and interactive terms of NE, SID Lys, CP, NDF, Lys:NE ratio, and BW (Table 4). The models predicted increased DP as NE increase for all four databases evaluated, with the magnitude of the response greater at lower NE levels than at higher levels (Figure 5). The improvement in dressing percentage plateaued at high NE levels with the NRC, CVB, and INRA models, but remained linear for the BR model.

The results described above were observed when a constant Lys:NE ratio was maintained. Interestingly, when the Lys:NE ratio was not maintained, almost no response to diet NE is predicted for DP using the NRC, INRA, and BR databases. The responses with the CVB database remained similar regardless of whether the Lys:NE ratio was maintained or not.

The dressing percentage response is in agreement with Nitikanchana et al. (2015) who increased NE levels and observed greater dressing percentage. Diets with low NE levels are commonly formulated with high dietary NDF content, which results in a reduction in BW and increase in the size and weight of the gastrointestinal tract, causing a reduction in dressing percentage (Asmus et al., 2014). Similar to the CVB model predictions, Marçal et al. (2019) observed increased dressing percentage when NE increased and Lys:NE ratio was not maintained. However, the predictions from the other three databases were similar to the results of others authors when maintaining the Lys:NE ratio constant as NE increased (De La Llata et al., 2001; 2007).

Backfat depth

For the four ingredient databases evaluated, the regression equation for BF with the lowest AIC included linear and quadratic terms of SID Lys, CP, and Lys:NE (Table 5). The model predicted a linear increase in BF as the NE increased for all four databases (Figure 6). The linear response was observed regardless of whether the Lys:NE ratio was maintained or not. However, the predicted increase in BF was greater when the Lys:NE ratio was not maintained and when the Lys level was below the estimated requirement (Figure 7). The model predictions are consistent with the literature, as it is well established that backfat depth increased as diet NE increase, regardless the ingredients used (Friesen et al., 1991; Apple et al., 2009; Royall et al., 2024). In addition, others have reported increased backfat depth when NE increased and SID Lys was not adjusted to maintain the Lys:NE ratio (De La Llata et al., 2007; Marçal et al., 2019; Bromm et al., 2023).

Loin depth

For the four ingredient databases evaluated, the regression equation for LD with the lowest AIC included linear, quadratic, and interactive terms of NE, SID Lys, CP, NDF, Lys:NE, and BW (Table 6). The models predicted a quadratic increase in loin depth as NE increase for the four databases (Figure 8), with a greater magnitude of the response at low NE levels and a diminishing response at high NE levels. The response observed was regardless of whether the Lys:NE was maintained or not; however, as the levels of SID Lys increased, the predicted loin depth response also increased (Figure 9).

Coble et al. (2018) observed that pigs fed a low NE diet containing 30% of DDGS and 19% of wheat middling, reduced the loin depth compared with pigs fed a corn-soybean meal-based diet. Salyer et al. (2012) also observed a reduction in LD when NE was reduced by adding 20% of wheat middlings to the diet. However, the reduction on LD with lower NE diets is not always consistent, with some studies not observing a reduction in LD as NE decreased by the use of high NDF ingredients (Smit et al., 2016; Royall et al., 2024). In contrast, the addition of fat or oil sources has been demonstrated to increase loin depth as NE increased whether the Lys:NE ratio was maintained (Beaulieu et al., 2009) or not (Smit et al., 2021). Therefore, our models' predictions seem to provide a reasonable estimate of how LD responds to changes in dietary compositions.

Percentage lean

For the four ingredient databases evaluated, the regression equation for PL with the lowest AIC included linear and quadratic terms of NE, SID Lys, CP, and NDF (Table 7). The model predicted a decrease in PL as the NE increased for the four ingredient databases (Figure 10). The magnitude of the reduction was greater at higher levels of NE than at low NE levels for

all the databases. The reductions were observed regardless of whether the Lys:NE ratio was maintained or not (Figure 11). However, the reduction in PL was greater when the Lys:NE ratio was not maintained. As would be expected, percentage lean estimates were greater with higher Lys levels than lower levels.

Royall et al. (2024) observed a linear increased in PL as NE decreased when adding fibrous ingredients to the diet of pigs from 25 to 135 kg. Beaulieu et al. (2009) reported a linear decreased in lean yield when increasing NE levels by adding tallow to a cereal-based diet fed to pigs from 30 to 120 kg. This is a result of the relationship between lean tissue accretion and backfat deposition in the carcass. Backfat deposition decreases as NE decreases in the diet, leading to an increase in PL. This response was demonstrated by Aymerich et al. (2020) who fed low and high levels of NE and SID Lys to finishing pigs and observed a reduced caloric intake with increased SID Lys intake with the low NE diet, resulting in greater PL.

Conclusion

The models developed with this meta-analysis included data from 94 experiments including a wide range of NE and ingredients using the nutrient values from NRC, CVB, INRA, and BR. The models can improve our ability to predict responses in growth performance and carcass characteristics to changes in dietary NE. The inputs necessary for the predictions are NE, CP, SID Lys, NDF, Lys:NE ratio, and BW.

Literature cited

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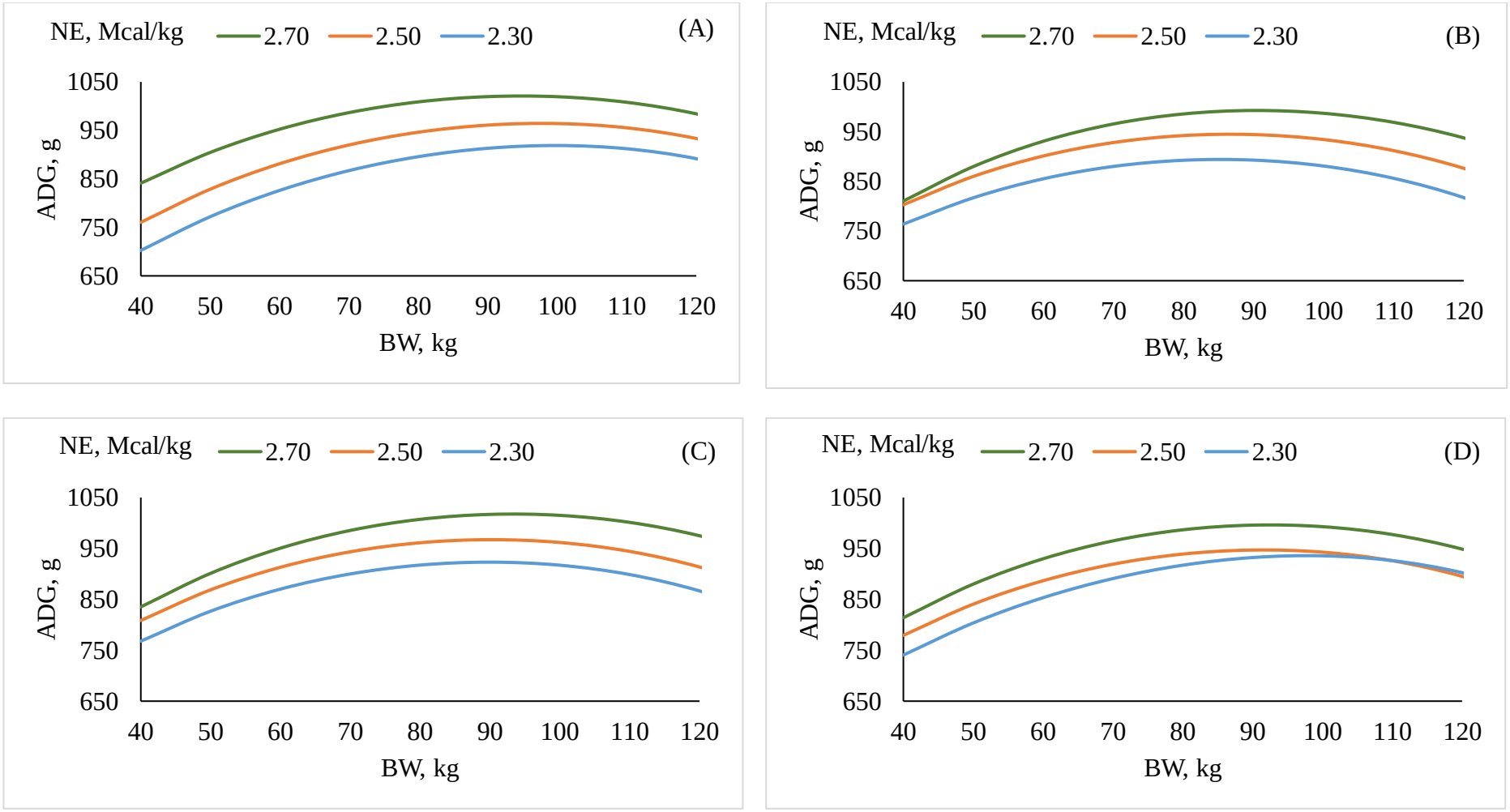

Figure 4.1. Predicted average daily gain (ADG) for 40 to 120 kg-pigs using values from NRC (A) , CVB (B), INRA (C), and BR (D) databases using a constant Lys to calorie ratio at three levels of NE.

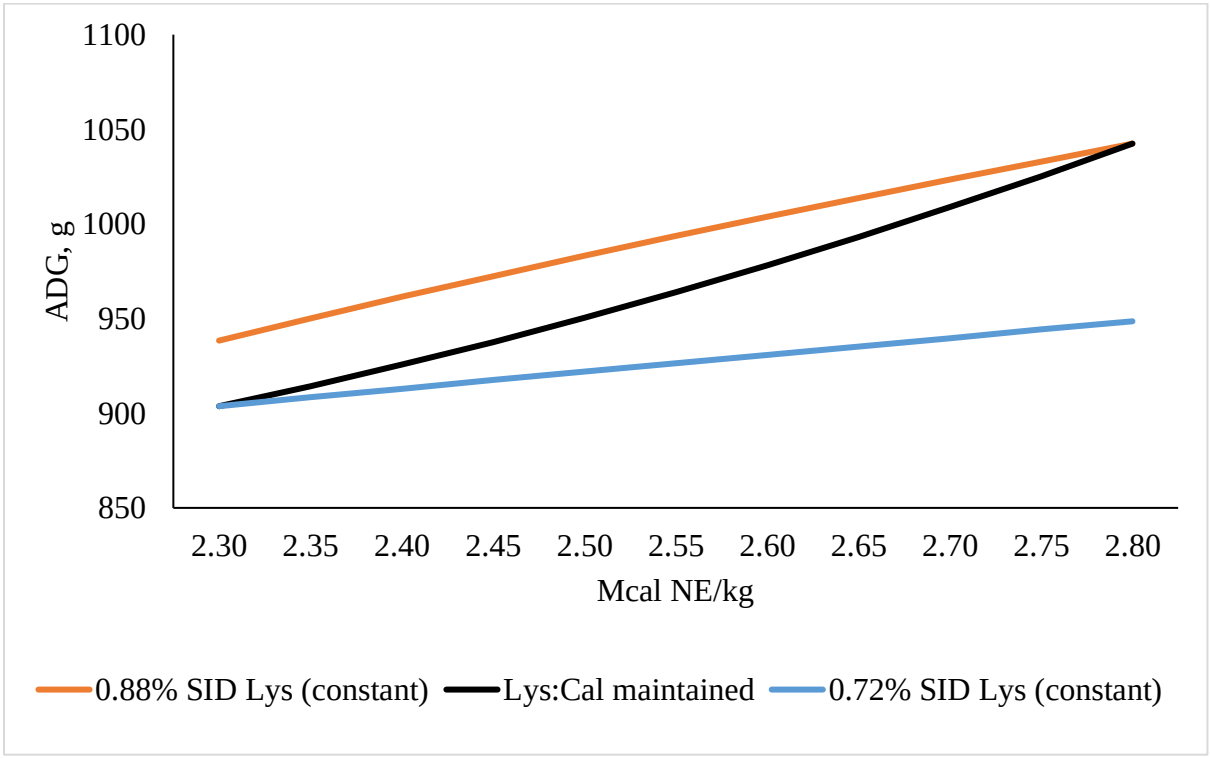

Figure 4.2. Predicted average daily gain (ADG) for 80 kg-pigs using values from NRC (2012) database using a constant SID Lys level to meet the required ratio at 2.3 Mcal NE (blue line), constant SID Lys level to meet the required ratio at 2.8 Mcal NE (orange line), or constant Lys to calorie ratio (black line).

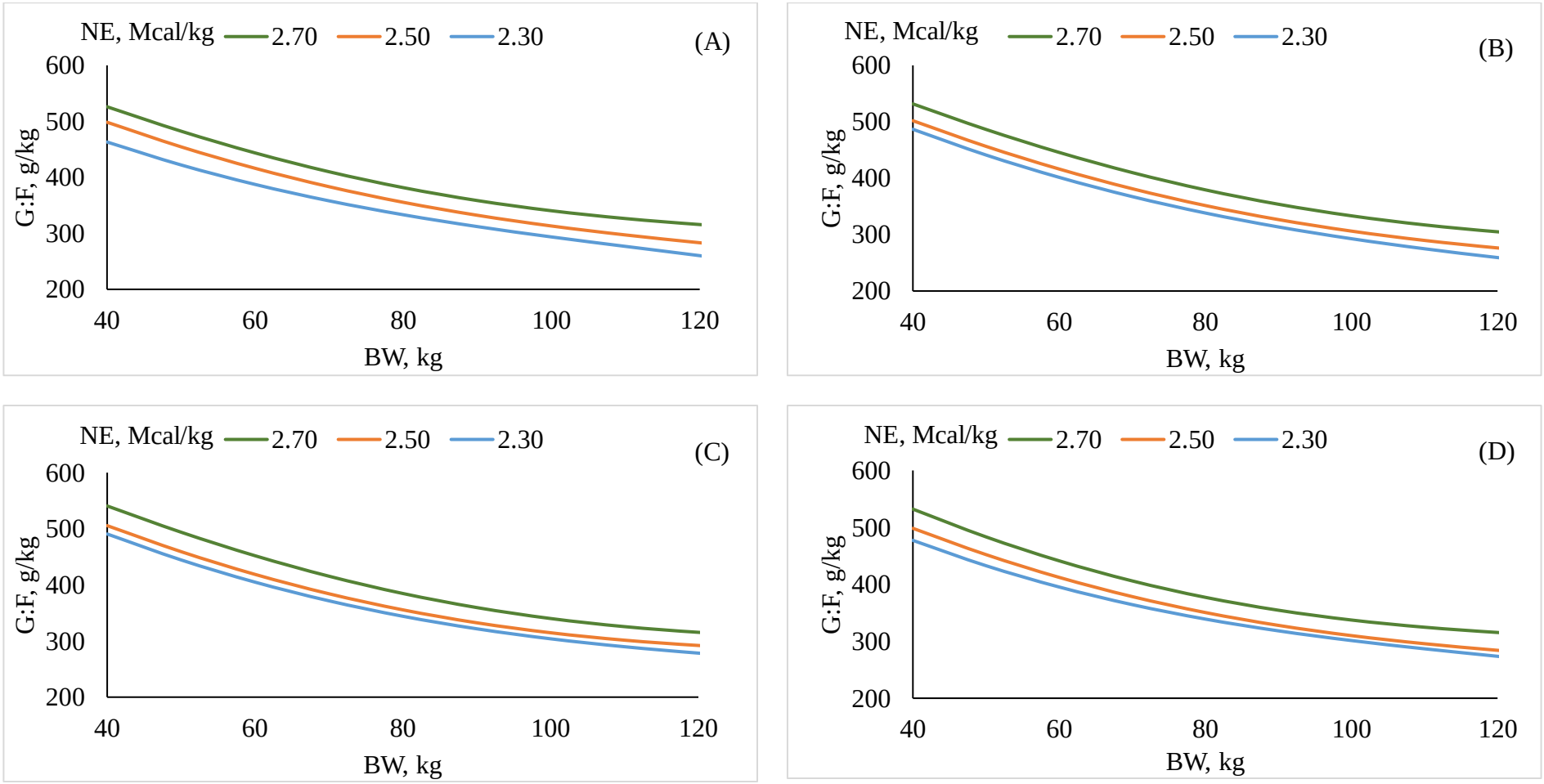

Figure 4.3. Predicted gain to feed ratio (G:F) for 40 to 120 kg-pigs using values from NRC (A) , CVB (B), INRA (C), and BR (D) databases using a constant Lys to calorie ratio at three levels of NE.

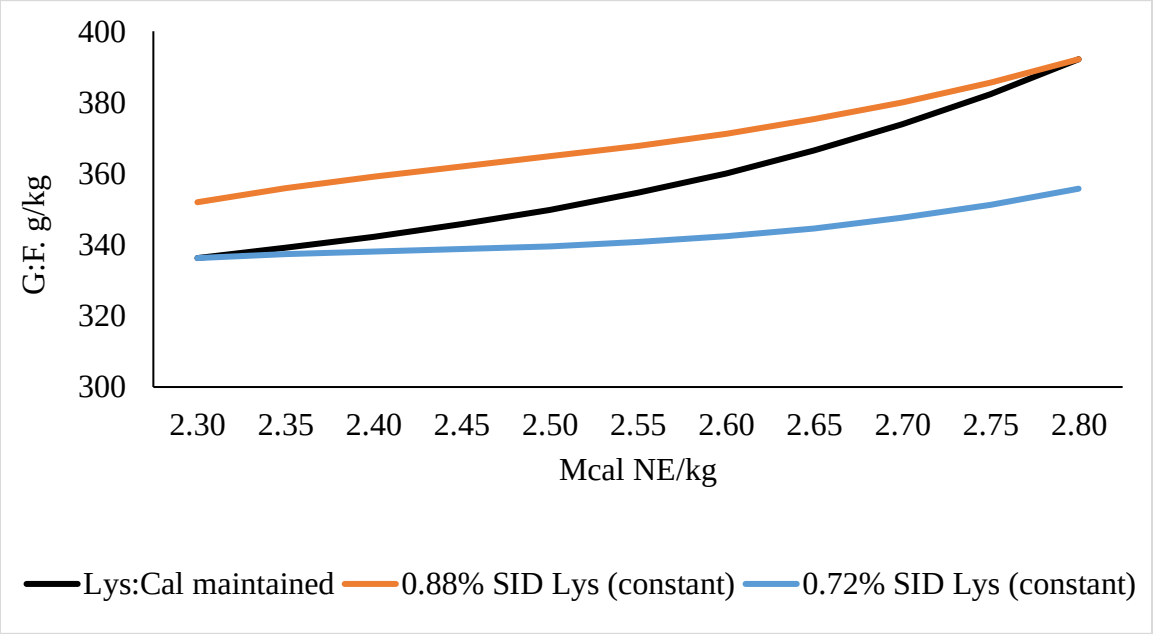

Figure 4.4. Predicted gain to feed ratio (G:F) for 80 kg-pigs using values from NRC (2012) database using a constant SID Lys level to meet the required ratio at 2.3 Mcal NE (blue line), constant SID Lys level to meet the required ratio at 2.8 Mcal NE (orange line), or constant Lys to calorie ratio (black line)

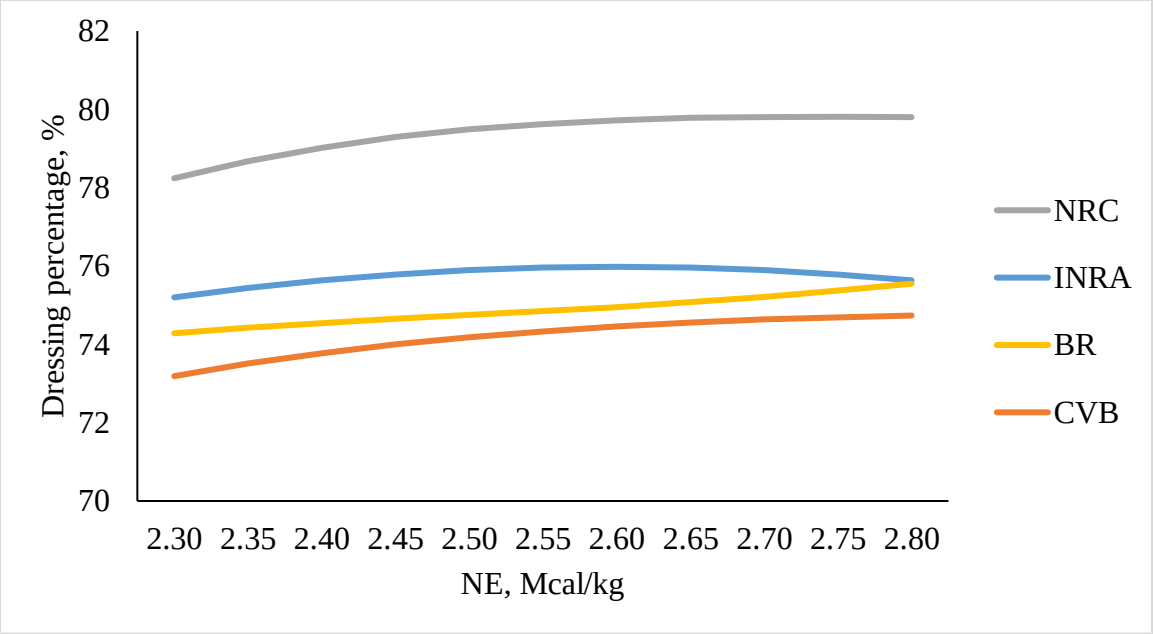

Figure 4.5. Predicted dressing percentage for 125 kg-marketed pigs using values from four different databases and constant Lys to calorie ratio with NE ranging from 2.30 to 2.80 Mcal/kg.

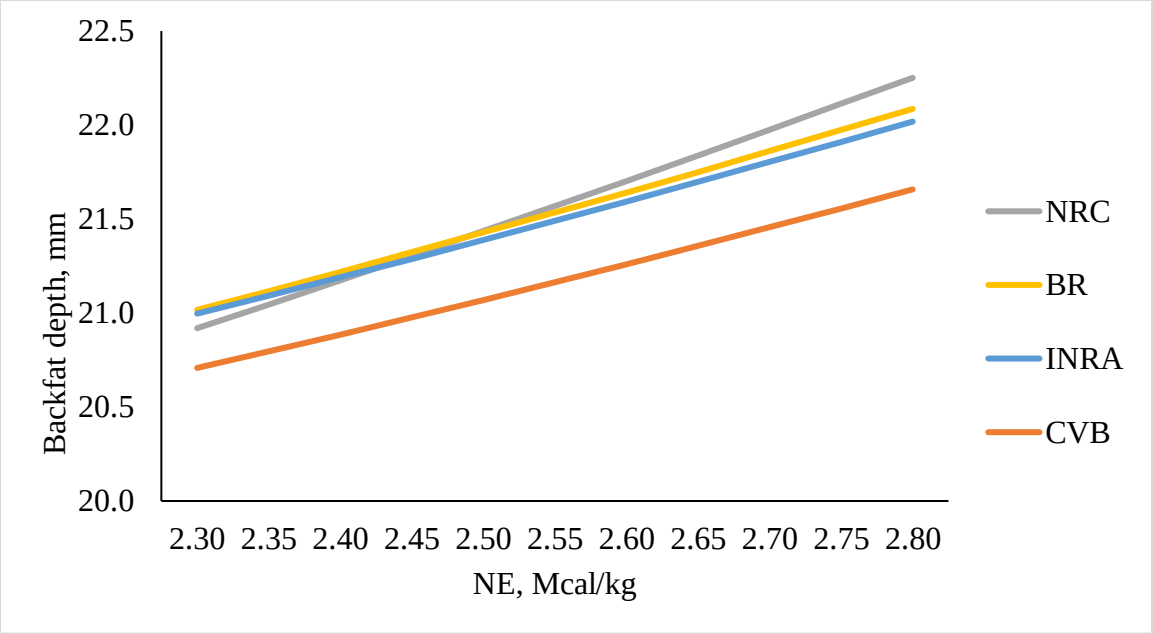

Figure 4.6. Predicted backfat depth for 125 kg-marketed pigs using values from four different databases and constant Lys to calorie ratio with NE ranging from 2.30 to 2.80 Mcal/kg.

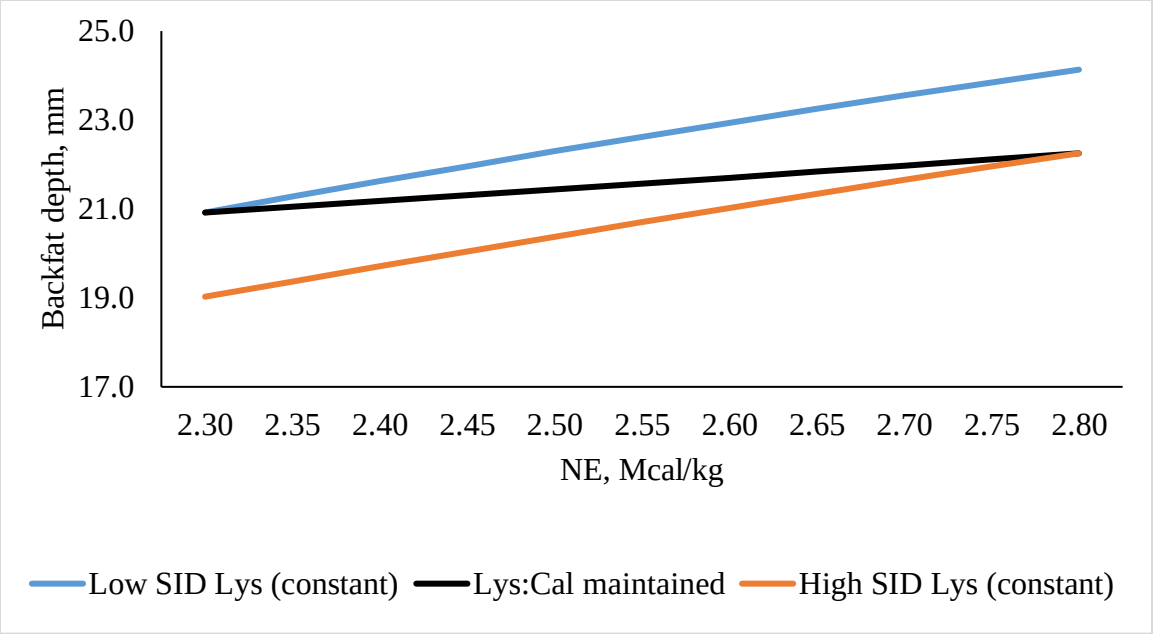

Figure 4.7. Predicted backfat depth for 125 kg-marketed pigs using values from NRC (2012) database using a constant SID Lys at the from requirement at 2.3 Mcal NE (blue line), constant SID Lys level at 2.8 Mcal NE (orange line), or constant Lys to calorie ratio (black line).

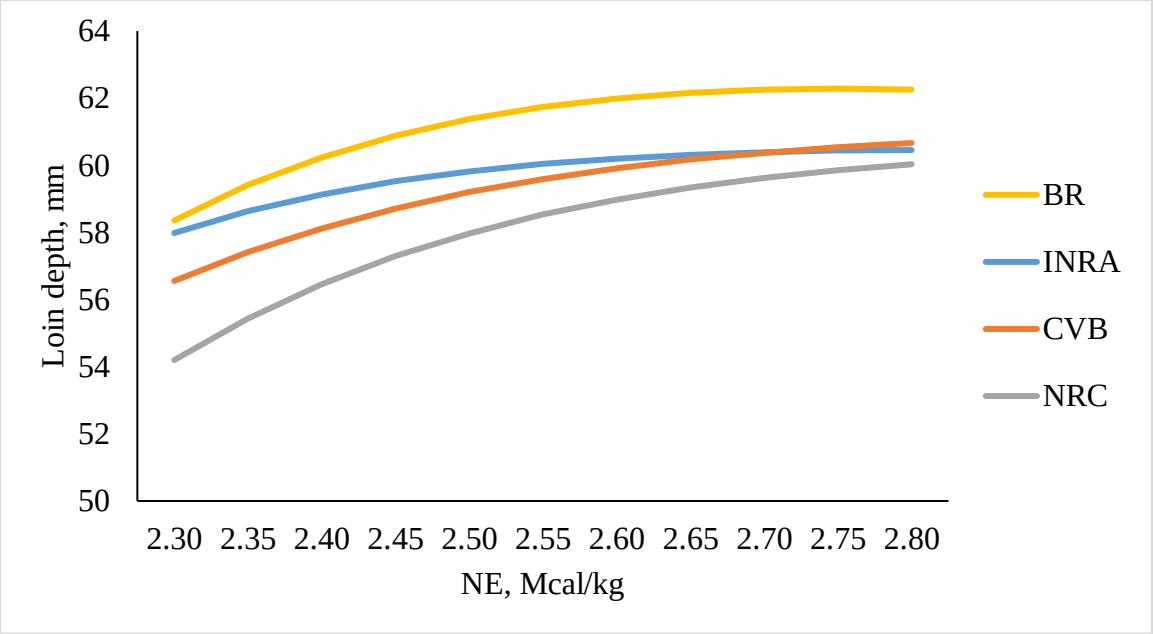

Figure 4.8. Predicted loin depth for 125 kg-marketed pigs using values from four different databases and constant Lys to calorie ratio with NE ranging from 2.30 to 2.80 Mcal/kg.

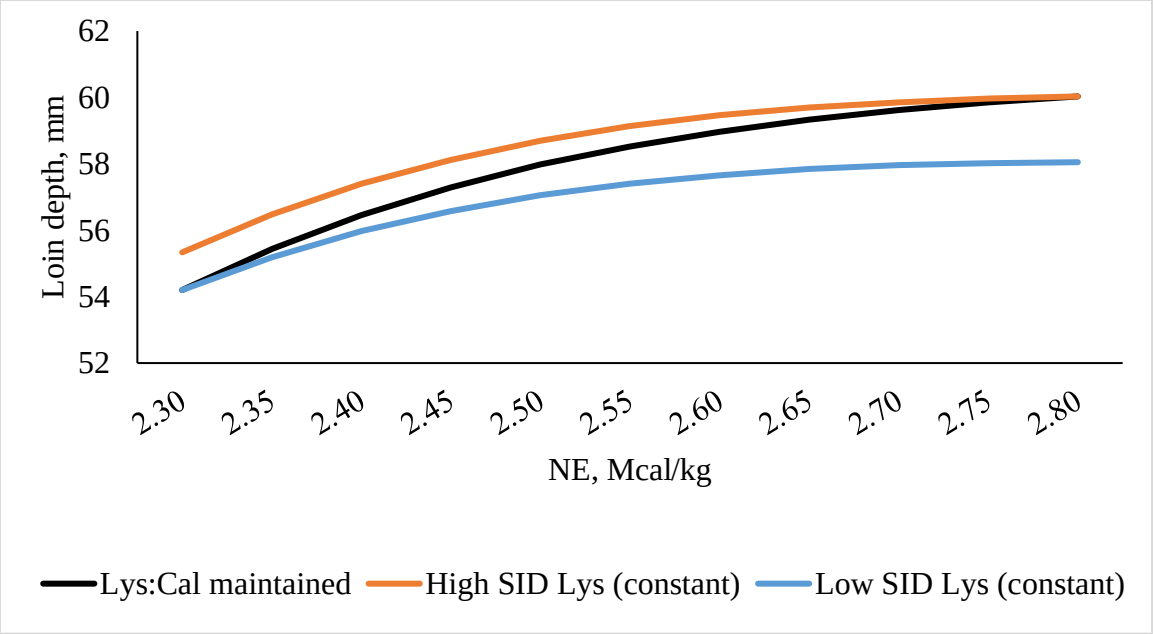

Figure 4.9. Predicted loin depth for 125 kg-marketed pigs using values from NRC (2012) database using a constant SID Lys at the from requirement at 2.3 Mcal NE (blue line), constant SID Lys level at 2.8 Mcal NE (orange line), or constant Lys to calorie ratio (black line).

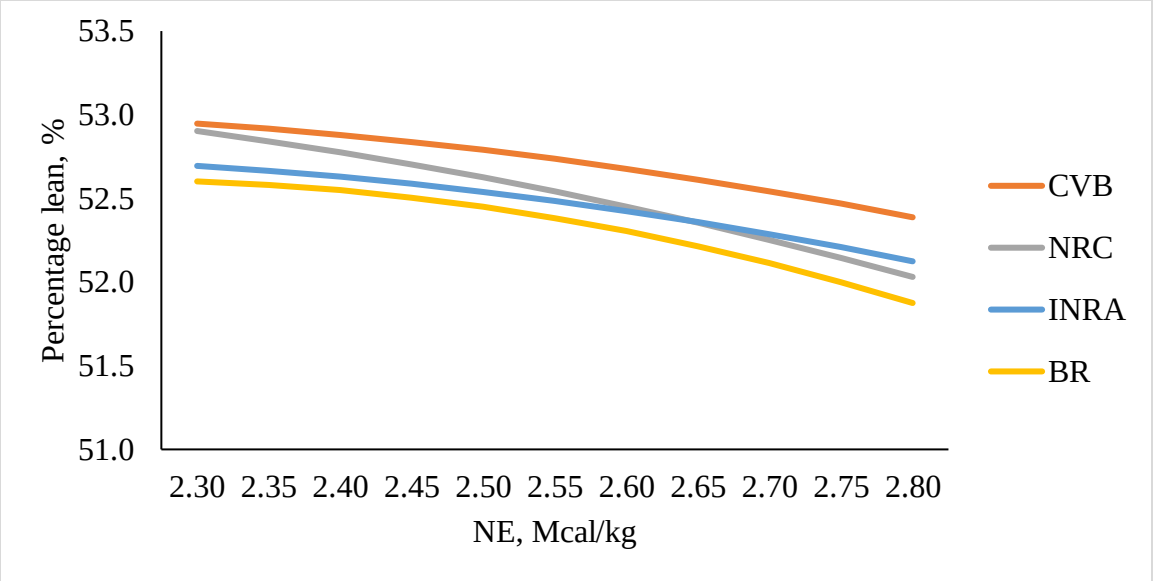

Figure 4.10. Predicted lean percentage for 125 kg-marketed pigs using values from four different databases and constant Lys to calorie ratio with NE ranging from 2.30 to 2.80 Mcal/kg.

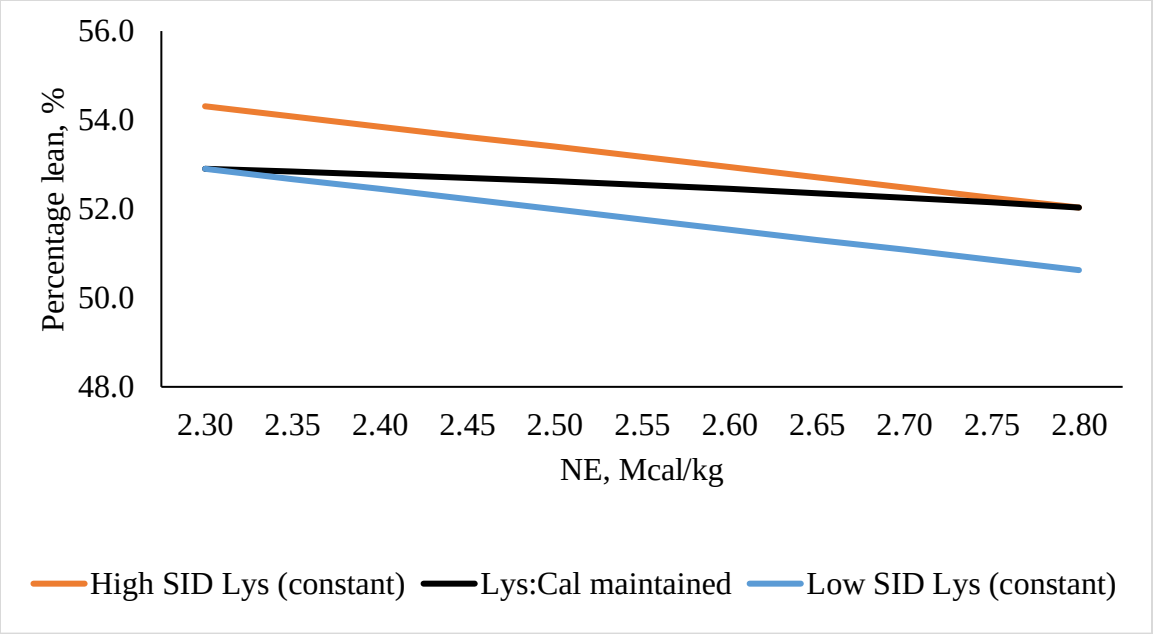

Figure 4.11. Predicted lean percentage for 125 kg-marketed pigs using values from NRC (2012) database using a constant SID Lys at the from requirement at 2.3 Mcal NE (blue line), constant SID Lys level at 2.8 Mcal NE (orange line), or constant Lys to calorie ratio (black line

Table 4.1. Summary of papers included in the regression analysis to predict growth performance from dietary nutrient levels on growing-finishing pigs.

Source	Source type	Trials	Sex[1]	Range of NE, kcal/kg[2]	Initial BW, kg	Final BW, kg	Diet[3]
Lopez-Bote et al., 1997	Journal	1	Both	2,508-2,660	30.5	90.1	Barley-SBM-CWG
Smith et al., 1997	Technical memo	1	Gilt	2,517-2,628	47.6	111.1	Corn-SBM-SBO
Knowles et al., 1998	Journal	3	Barrow, gilt	2,503-2,710	74.0, 70.0, 70.0	117.0, 101.5, 111.2	Corn-SBM-Poultry fat
Smith et al., 1999	Journal	1	Gilt	2,517-2,628	29.2	107.0	Corn-SBM-CWG
De la Llata et al., 2001	Journal	1	Both	2,397-2,783	36.0	120.0	Corn-SBM-CWG
Engel et al., 2001	Journal	1	Gilt	2,525-2,850	60.3	110.6	Corn-SBM-CWG-Poultry fat
Baudon et al., 2003	Technical memo	1	Both	2,471-2,812	57.6	127.0	Corn-SBM-SBO
Kerr et al., 2003	Journal	1	Gilt	2,395-2,537	25.3	109.7	Corn-SBM-WM -Tallow
Shriver et al., 2003	Journal	1	Both	2,492-2,651	28.4	114.2	Corn-SBM-SH
Young et al., 2003	Technical memo	1	Both	2,502-2,749	71.6	105.2	Corn-SBM-CWG
Hastad et al., 2005	Journal	1	Both	2,484-2,755	50.1	117.0	Corn-SBM-CWG-Nutridense corn
Benz et al., 2007	Technical memo	1	Both	2,499-2,727	54.4	136.5	Corn-Sorghum-SBM-CWG
De la Llata et al., 2007	Journal	2	Gilt, barrow	2,449-2,787	25.0, 34.0	120.0, 120.0	Corn-SBM-CWG

Duttlinger et al., 2008	Technical memo	1	Both	2,559-2,835	77.7	101.7	Corn-SBM-CWG
Apple et al., 2009	Journal	1	Mixed	2,481-2,795	28.1	113.6	Corn-SBM-Tallow-Poultry fat-SBO
Beaulieu et al., 2009	Journal	2	Both	2,188-2,551	31.0, 36.8	115, 94.3	Barley-wheat-SBM-Canola meal-Canola oil-Tallow
Jin et al., 2010	Journal	1	Mixed	2,480-2,669	58.5	103.8	Corn-SBM-WB-Copra meal-CGM-SBM
Xu et al., 2010a	Journal	1	Mixed	2,486-2,520	29.9	127.8	Corn-SBM-Corn DDGS
Xu et al., 2010b	Journal	1	Both	2,491-2,526	22.0	115.6	Corn-SBM-Corn DDGS
Barnes et al, 2011	Technical memo	1	Mixed	2,399-2,623	48.1	124.8	Corn-SBM-Corn DDGS-WM-CWG
Benz et al., 2011	Journal	1	Both	2,499-2,727	44.0	125.2	Corn-SBM-CWG-SBO
Chen et al., 2011	Journal	2	Barrow	2,330-2,703	69.0, 62.0	95.0, 101.0	Corn-SBM-Wheat bran-SBO
Chu et al., 2012	Journal	3	Mixed	2,250-2,648	20.8, 57.0, 78.6	55.9, 76.6, 105.8	Corn-SBM-Wheat bran-SBO
Jungst et al., 2012	Technical memo	1	Mixed	2,367-2,708	30.0	137.1	Corn-SBM-Corn DDGS-WM-CWG
Lee et al., 2012	Journal	1	Mixed	2,426-2,663	40.9	126.4	Corn-SBM-Corn DDGS-Corn germ

Park et al., 2012	Journal	1	Mixed	2,513-2,554	70.1	104.8	Corn-SBM-Wheat-WB-Tallow-Coconut oil-Olive oil-SBO
Salyer et al., 2012	Journal	2	Mixed	2,422-2,709	45.0, 42.0	134.9, 136.9	Corn-SBM-Corn DDGS-WM
Graham et al., 2013	Technical memo	1	Mixed	2,436-2,499	46.3	121.7	Corn-SBM-Corn DDGS
Hilbrands et al., 2013	Journal	1	Mixed	2,433-2,454	51.3	112.2	Corn-SBM-Corn DDGS
Kim et al., 2013	Journal	1	Barrow	2,496-2,565	36.2	82.4	Corn-SBM-WM-Corn DDGS- Canola meal-Palm kernel meal-Molasses-Tallow
Permentier et al., 2013	Journal	1	Mixed	2,284-2,467	21.5	105.4	Corn-Barley-Wheat-SBM-WB-Wheat gluten feed-Hominy feed-Bakery meal-Canola meal-Sunflower meal-Tallow
Pompeu et al., 2013	Journal	1	Mixed	2,603-2,636	100.3	126.0	Corn-SBM-Corn DDGS-CWG
Stewart et al., 2013	Journal	1	Barrow	2,038-2,597	25.2	124.9	Corn-SBM-SH-WM-SBO

Suarez-Belloch et al., 2013	Journal	1	Gilt	2,322-2,452	93.9	129.7	Corn-Barley-SBM-WB-Canola meal-Tallow
Asmus et al., 2014	Journal	1	Mixed	2,350-2,509	41.0	121.6	Corn-SBM-Corn DDGS-WM
Doti et al., 2014	Journal	1	Gilt	2,319-2,384	63.0	94.6	Corn-Barley-Rice-Field peas-SBM-SH-Tallow
Graham et al., 2014	Journal	1	Mixed	2,374-2,549	55.7	126.8	Corn-SBM-Corn DDGS-WM
Joven et al., 2014	Journal	1	Gilt	2,071-2,251	69.3	98.7	Barley-SBM-Olive cake-Sunflower oil
Richert et al., 2014[2]	Journal	1	Barrow	2,325-2,566	28.4	137.5	Corn-SBM-Corn DDGS-WM-SH
Smit et al., 2014	Journal	1	Both	2,369-2,383	29.9	117.0	Wheat-Barley- Field pea-SBM-Wheat- Corn DDGS-Tallow
Stephenson et al., 2014	Technical memo	1	Mixed	2,519-2,698	45.7	132.6	Corn-SBM-Tallow-SBO
Zhou et al., 2014	Journal	1	Both	2,247-2,257	38.3	113.2	Wheat-Lentil-SBM-Wheat DDGS-Expelled canola
Davis et al., 2015	Journal	1	Mixed	2,442-2,699	32.0	114.6	Corn-SBM-Corn DDGS-Tallow
Little et al., 2015	Journal	1	Mixed	2,509-2,579	28.0	114.2	Corn-SBM-Canola meal-SBO

Nemechek et al., 2015	Journal	1	Mixed	2,359-2,651	48.5	131.4	Corn-SBM-Corn DDGS-WM-Corn oil
Nitikanchana et al., 2015	Journal	1	Mixed	2,276-2,662	56.9	128.3	Corn-SBM-Corn DDGS-WM-SH-CWG
Schinckel et al., 2015	Journal	1	Barrow	2,325-2,566	28.4	135.8	Corn-SBM-Corn DDGS-WM-SH-CWG
Sotak et al., 2015	Journal	1	Mixed	2,433-2,585	58.8	133.3	Corn-SBM-Corn DDGS-Sorghum DDGS
Camara et al., 2016	Journal	1	Mixed	2,389-2,527	47.9	104.3	Barley-Rye-Wheat-SBM-Canola meal-CWG
Cline et al., 2016	Journal	1	Barrow	2,109-3,029	85.0	120.7	Corn-SBM-Poultry fat
Smit et al., 2016	Journal	1	Both	2,067-2,391	28.9	125.5	Wheat-Barley-Oats-Field pea-SBM-Wheat DDGS-Canola oil
Adhikari et al., 2017	Journal	1	Mixed	2,414-2,698	24.7	110.5	Corn-SBM-Flaxseed oil-Poultry fat
Coble et al., 2017	Journal	1	Mixed	2,522-2,742	105.6	125.8	Corn-SBM-Corn DDGS-Tallow-CWG
Lei et al., 2018	Journal	1	Barrow	2,409-2,617	27.1	121.3	Corn-Wheat-SBM-Molasses-SBO
Pangeni et al., 2017	Journal	1	Both	2,470-2,596	45.5	113.2	Corn-SBM-Fish meal-Tallow-CWG

Villela et al., 2017	Journal	1	Mixed	2,356-2,679	23.6	124.3	Corn-SBM-Corn DDGS-Cottonseed oil
Clarke et al., 2018	Journal	1	Both	2,332-2,667	47.5	107.5	Corn-Wheat-Barley-SBM-Corn DDGS-Canola meal-SBO
Coble et al., 2018	Journal	2	Mixed	2,372-2,518	38.3, 44.5	126.0, 132.5	Corn-SBM-Corn DDGS-WM
Liu et al., 2018	Journal	2	Barrow	2,528-2,802	63.6, 71.2	123.8, 132.6	Corn-SBM-SBO-CWG-Palm oil-A/V blend-Tallow
Smit et al., 2018	Journal	1	Both	2,225-2,422	32.8	107.8	Wheat-Barley-Faba bean-Expelled soybean-Canola meal-Wheat DDGS-Canola oil
Fang et al., 2019	Journal	1	Mixed	2,422-2,591	31.0	108.2	Corn-SBM-WB-Palm kernel meal-Tallow
Yin et al., 2019	Journal	1	Mixed	2,437-2,474	25.5	57.5	Corn-Wheat-SBM-Corn DDGS-Canola meal-Molasses-Tallow
Aymerich et al., 2020	Journal	2	Both	2,349-2,524	19.8	122.0	Corn-Wheat-Barley-SBM-WM-Sunflower meal-CWG-Palm oil

Hastad et al., 2020	Journal	2	Gilt	2,444-2,737	30.7, 35.1	119.0, 120.0	Corn-SBM-CWG
van der Peet-Schwering et al., 2020	Technical memo	1	Barrow	2,247-2,488	52.1	128.6	Corn-Wheat-Barley-SBM-Molasses-Corn starch-Oat hulls-Wheat straw-SBO-Palm oil
Hilbrands et al., 2021	Journal	1	Mixed	2,433-2,454	35.1	126.4	Corn-SBM-Camelina cake
Huang et al., 2021	Journal	2	Mixed	2,566-2,614	27.8, 55.3	55.4, 101.1	Corn-SBM-DFRB-SBO
Rao et al., 2021	Journal	1	Mixed	2,455-2,553	27.1	130.0	Corn-SBM-Corn DDGS-HPDDGS
Smit et al., 2021	Journal	1	Both	2,208-2,454	30.9	115.5	Wheat-Barley-Field pea-Wheat DDGS-Canola oil
Bromm et al., 2022	Technical memo	1	Mixed	2,498-2,572	31.3	123.2	Corn-SBM-Expelled soybean-Corn DDGS
Gaffield et al., 2022	Journal	1	Both	2,407-2,828	30.3	130.3	Corn-SBM-Corn DDGS-SBO
Becker et al., 2023	Journal	1	Both	2,494-2,798	40.8	135.3	Corn-SBM-Tallow-CWG-Corn oil-Flaxseed oil
Bromm et al., 2023	Journal	2	Mixed	2,476-2,675	37.3	129.6	Corn-SBM-Corn DDGS-CWG-Corn oil

Hagen et al., 2023	Journal	1	Mixed	2,521-2,663	65.1	119.1	Corn-SBM-Corn DDGS-Corn oil
Smit et al., 2023	Journal	1	Both	2,338-2,463	70.1	128.4	Rye-Wheat-Barley-Canola meal-Canola oil
Zhao et al., 2023	Journal	1	Mixed	2,014-2,451	21.1	35.5	Corn-SBM-SH
Royall et al., 2024	Journal	1	Mixed	2,276-2,534	23.3	140.4	Corn-SBM-Corn DDGS-WM

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

[2] Energy range after reformulating diets using the NRC (2012) ingredient database.

[3] A/V= animal/vegetable; CGM= corn gluten meal; CWG= choice white grease; DDGS= dried distiller grains with solubles; DFRB= defatted rice bran; HPDDGS= high protein dried distiller grains with solubles; SBM= soybean meal; SBO= soybean oil; SH= soybean hulls; WB= wheat bran; WM= wheat middlings.

Table 4.2. Regression equations to predict ADG (g) from dietary nutrients values calculated using NRC (2012), CVB (2022), INRA (2024), and Rostagno et al. (BR; 2024) databases

Database	Model[1]
NRC	= -1619.2980797296 + 25.9248064834 × NE - 2657.6209162609 × SID Lys + 123.0469725298 × CP - 9.2854579989 × NDF + 872.0182830582 × Lys:NE + 26.664395965 × BW + 2599.7646012325 × SID Lys × SID Lys - 0.1016237102 × BW × BW - 71.8618465276 × SID Lys × CP - 607.1294449572 × SID Lys × Lys:NE + 25.6463076451 × SID Lys × BW - 0.8399854508 × CP × BW + 0.0967347393 × NDF × BW - 5.2553838048 × Lys:NE × BW
CVB	= -1814.4384112041 + 206.517524479 × NE - 778.1983728868 × SID Lys + 129.6301073201 × CP + 80.4647404985 × NDF + 282.3563876351 × Lys:NE + 24.7659153551 × BW - 3384.4319037348 × SID Lys × SID Lys - 2.2762855586 × CP × CP - 243.7787219367 × Lys:NE × Lys:NE - 0.0975386131 × BW × BW - 33.9441904999 × NE × NDF + 1757.4727814576 × SID Lys × Lys:NE + 19.1642834014 × SID Lys × BW - 0.6718966626 × CP × BW - 3.9494557049 × Lys:NE × BW
INRA	= -1999.9820303976 + 230.7944320121 × NE - 2727.9930193314 × SID Lys + 121.5107460754 × CP + 23.423335734 × NDF + 874.7233308056 × Lys:NE + 25.3853920238 × BW - 153.4238944185 × Lys:NE × Lys:NE - 0.1002967447 × BW × BW - 13.6394673306 × NE × NDF - 71.9079043803 × SID Lys × CP + 662.9458753902 × SID Lys × Lys:NE + 25.6123365351 × SID Lys × BW - 0.8195651237 × CP × BW + 0.1103615852 × NDF × BW - 5.2257322249 × Lys:NE × BW
BR	= -2187.8273930705 + 583.0117896299 × NE - 6777.4437659115 × SID Lys + 67.8540358961 × CP + 126.4572974911 × NDF + 1668.261887824 × Lys:NE + 23.0314156223 × BW + 2858.6054468201 × SID Lys × SID Lys - 0.1052650197 × BW × BW + 26.1891445104 × NE × CP - 74.7164099573 × NE × NDF - 74.2218740238 × SID

	Lys × CP + 221.0203991623 × SID Lys × NDF - 631.7283787359 × SID Lys × Lys:NE + 36.6799802803 × SID Lys × BW - 0.9017427043 × CP × BW - 45.3858825952 × NDF × Lys:NE + 0.3385531769 × NDF × BW - 7.691336015 × Lys:NE × BW

[1] BW= kg; CP= %; NDF= %; NE= Mcal/kg; Lys:NE= g/Mcal; SID Lys= %.

Table 4.3. Regression equations to predict G:F (g/kg) from dietary nutrients values calculated using NRC (2012), CVB (2022), INRA (2024), and Rostagno et al. (BR; 2024) databases

Database	Model[1]
NRC	= -232.8670000513 - 102.0339177026 × NE + 1386.8135453223 × SID Lys - 3.1583174866 × CP + 80.3303777865 × NDF - 115.1570451563 × Lys:NE + 4.1836503117 × BW + 2553.6417073224 × SID Lys × SID Lys + 228.757399518 × Lys:NE × Lys:NE + 12.736240264 × NE × CP - 24.4502664605 × NE × NDF - 23.0415882284 × SID Lys × CP + 101.5847297779 × SID Lys × NDF - 1559.9331198689 × SID Lys × Lys:NE - 3.9239483753 × SID Lys × BW - 0.1078600966 × CP × BW - 28.1879330488 × NDF × Lys:NE - 0.1153929924 × NDF × BW
CVB	= 99.7461728947 - 113.3083770952 × NE + 935.8795699539 × SID Lys - 17.2966778738 × CP + 94.9774619186 × NDF - 37.9762425086 × Lys:NE - 2.0161722086 × BW + 1610.4531944512 × SID Lys × SID Lys + 159.74542697 × Lys:NE × Lys:NE + 0.0052380663 × BW × BW + 12.4775154794 × NE × CP - 31.1237068567 × NE × NDF + 1.2427111286 × NE × BW - 13.1266040224 × SID Lys × CP + 119.2699792638 × SID Lys × NDF - 1060.7739126166 × SID Lys × Lys:NE - 3.6935356416 × SID Lys × BW - 32.0654529626 × NDF × Lys:NE - 0.0911980319 × NDF × BW
INRA	= -703.7750040199 + 119.4882767145 × NE + 835.7632301112 × SID Lys - 7.9978781212 × CP + 133.0300089997 × NDF - 16.2025563793 × Lys:NE + 2.5839569796 × BW + 1473.0831052217 × SID Lys × SID Lys - 0.3005294011 × NDF × NDF +153.1415106747 × Lys:NE × Lys:NE + 0.0055228756 × BW × BW + 13.0382872278 × NE × CP - 42.3250340064 × NE × NDF - 20.824228555 × SID Lys × CP + 129.4974306693 × SID Lys × NDF - 983.0906625525 × SID Lys × Lys:NE - 3.1673336793× SID Lys × BW - 0.0681222203 × CP × BW - 34.0726676578 × NDF × Lys:NE - 0.1438990922 × NDF × BW

BR	= 4909.7943147223 - 3761.644203275 × NE + 23001.8334436392 × SID Lys - 9.8071505725 × CP + 95.2319397759 × NDF - 2851.9080444202 × Lys:NE - 4.9992090027 × BW + 690.2609687271 × NE × NE + 8101.9257984486 × SID Lys × SID Lys + 552.2533706835 × Lys:NE × Lys:NE - 4396.8855769421 × NE × SID Lys + 16.2436511215 × NE × CP - 39.7585040665 × NE × NDF + 3.0644930508 × NE × BW - 23.272581973 × SID Lys × CP + 127.9603281409 × SID Lys × NDF - 4232.938154975 × SID Lys × Lys:NE - 3.479020422 × SID Lys × BW - 0.1202766421 × CP × BW - 30.1892271442 × NDF × Lys:NE

[1] BW= kg; CP= %; NDF= %; NE= Mcal/kg; Lys:NE= g/Mcal; SID Lys= %.

Table 4.4. Regression equations to predict dressing percentage from dietary nutrients values calculated using NRC (2012), CVB (2022), INRA (2024), and Rostagno et al. (BR; 2024) databases

Database	Model[1]
NRC	= 51.6684755267 + 7.1030096064 × NE + 54.0870565413 × SID Lys + 1.6439820046 × CP + 0.4039153805 × NDF - 20.5375389219 × Lys:NE + 0.2869358688 × BW - 0.016597667 × NDF × NDF - 0.1531408962 × NE × BW - 4.8153797375 × SID Lys × CP + 0.5304361357 × SID Lys × BW + 0.9830652207 × CP × Lys:NE - 0.0127129553 × CP × BW
CVB	= 20.7694238154 + 8.8368132085 × NE + 29.8499609182 × SID Lys + 2.7638720127 × CP + 0.3157181262 × NDF - 7.6845707306 × Lys:NE + 0.6810614702 × BW - 0.0140236798 × NDF × NDF - 0.0034305124 × BW × BW - 1.1550263852 × NE × CP
INRA	= -38.9437370042 + 42.3280400717 × NE - 14.0312997305 × SID Lys + 5.1358966957 × CP + 0.303065818 × Lys:NE + 0.7172164329 × BW - 3.9232938916 × NE × NE - 0.0024059237 × BW × BW - 1.2136149678 × NE × CP - 0.1022918451 × NE × BW + 0.3769199801× SID Lys × BW - 0.2780237664 × CP × Lys:NE - 0.0176470443 × CP × BW
BR	= 60.381934141 - 6.5509311762 × NE + 63.1408602487 × SID Lys + 2.240809544 × CP - 0.3086006488 × NDF - 19.6261681279 × Lys:NE + 0.4599315265 × BW - 0.0069494853 × NDF × NDF - 0.0028748829 × BW × BW - 4.5570169494 × SID Lys × CP + 0.3779286046 × SID Lys × BW + 0.8766520394 × CP × Lys:NE - 0.0180112941 × CP × BW + 0.0059356777 × NDF × BW

[1] BW= kg; CP= %; NDF= %; NE= Mcal/kg; Lys:NE= g/Mcal; SID Lys= %.

Table 4.5. Regression equations to predict backfat depth (mm) from dietary nutrients values calculated using NRC (2012), CVB (2022), INRA (2024), and BR (2024) databases

Database	Model[1]
NRC	= 41.4410513954 + 14.8656283053 × SID Lys - 0.6326892081 × CP - 12.1380129342 × Lys:NE - 0.0133880688 × CP × CP + 1.1112817574 × Lys:NE × Lys:NE
CVB	= 40.773470245 + 11.2096938112 × SID Lys - 0.6289554285 × CP - 11.4850256912 × Lys:NE + 0.0155582645 × CP × CP + 1.2067344764 × Lys:NE × Lys:NE
INRA	= 41.8611843628 + 12.0910802714 × SID Lys - 0.6391376642 × CP - 12.04402346 × Lys:NE + 0.0150028087 × CP × CP + 1.2515998564 × Lys:NE × Lys:NE
BR	= 41.4305258941 + 11.8818260729 × SID Lys - 0.591794295 × CP - 11.5860163961 × Lys:NE + 0.0145594304 × CP × CP + 1.0995327615 × Lys:NE × Lys:NE

[1] BW= kg; CP= %; NDF= %; NE= Mcal/kg; Lys:NE= g/Mcal; SID Lys= %.

Table 4.6. Regression equations to predict loin depth (mm) from dietary nutrients values calculated using NRC (2012), CVB (2022), INRA (2024), and Rostagno et al. (BR; 2024) databases

Database	Model[1]
NRC	= -16.7992454106 + 17.2658536059 × NE - 106.6634904715 × SID Lys + 0.1550376119 × CP - 0.0727312562 × NDF + 48.6541457906 × Lys:NE - 0.1535643762 × CP × CP - 0.0358142801 × NDF × NDF - 5.4618633046 × Lys:NE × Lys:NE + 4.2267870055 × SID Lys × CP - 2.0313848595 × SID Lys × NDF + 0.1484978883 × CP × NDF
CVB	= -19.5516783865 + 17.2049423856 × NE - 119.782765812 × SID Lys - 2.280874011 × CP - 0.5061736313× NDF + 63.3574933726 × Lys:NE + 0.20000727 × BW - 0.1410559031 × CP × CP - 0.0317751306 × NDF × NDF - 5.7210770504 × Lys:NE × Lys:NE + 4.6268866721 × SID Lys × CP - 1.4517624435 × SID Lys × NDF + 0.140884721 × CP × NDF + 0.0196745175 × CP × BW - 0.1611361067 × Lys:NE × BW
INRA	= -12.0983887068 + 15.8195346127 × NE - 86.1273297053 × SID Lys - 0.2953637449 × CP + 0.1063604106 × NDF + 44.9157279301 × Lys:NE - 0.1159493423 × CP × CP - 0.0299121743 × NDF × NDF - 5.1049451749 × Lys:NE × Lys:NE + 3.2478151646 × SID Lys × CP - 1.5857085004 × SID Lys × NDF + 0.1159313903 × CP × NDF
BR	= 21.8690093659 - 10.2109601057 × NE + 120.5048939972 × SID Lys - 0.8395053171 × CP - 0.6824659273 × NDF + 7.5832136399 × Lys:NE + 0.4891266842 × BW - 73.2950916578 × SID Lys × SID Lys - 0.1329114022 × CP × CP - 0.0237373621 × NDF × NDF + 3.5615247659 × SID Lys × CP - 2.104912247 × SID Lys × NDF + 0.1550707755 × CP × NDF + 0.0055168017 × NDF × BW - 0.193344761 × Lys:NE × BW

[1] BW= kg; CP= %; NDF= %; NE= Mcal/kg; Lys:NE= g/Mcal; SID Lys= %.

Table 4.7. Regression equations to predict percentage lean from dietary nutrients values calculated using NRC (2012), CVB (2022), INRA (2024), and Rostagno et al. (BR; 2024) databases

Database	Model[1]
NRC	= 49.3215904687 - 4.5564383267 × NE + 31.3355706686 × SID Lys + 0.0864922401 × CP - 16.201377828 × SID Lys × SID Lys
CVB	= 48.4640944619 - 3.7177041183 × NE + 29.6200534702 × SID Lys + 0.0504953026 × CP - 15.1352893455 × SID Lys × SID Lys
INRA	= 47.465852211 - 3.7909777756 × NE + 31.6810093076 × SID Lys + 0.0765284096 × CP - 16.7866590204 × SID Lys × SID Lys
BR	= 51.7488857451 - 4.9347317776 × NE + 28.2365223351 × SID Lys + 0.0727058095 × CP - 0.0390509611 × NDF - 13.6571465659 × SID Lys × SID Lys

[1] BW= kg; CP= %; NDF= %; NE= Mcal/kg; Lys:NE= g/Mcal; SID Lys= %.

Chapter 5 - Comparison of central composite design and factorial arrangement to evaluate the interaction between net energy, soybean meal, and standardized ileal digestible lysine content of diets fed to pigs from 11 to 25 kg

Abstract

Two studies compared a central composite design (CCD) and a factorial arrangement of treatments to evaluate the effects of dietary net energy (NE), soybean meal (SBM), and standardized ileal digestible (SID) Lys on growth performance of 11 to 25 kg pigs. In Exp. 1, a CCD used 4,681 (PIC 337 × 1050; initially 13.0 kg) with 35 pigs per pen and 7 pens of the factorial and axial points and 35 pens of the central point. Eight diets were formulated to various NE, SBM, and SID Lys concentrations then blended to create the 15 dietary treatments. Net energy ranged from 2,334 to 2,762 kcal/kg, SBM from 25.5 to 35.9%, and SID Lys from 1.08 to 1.52%. Increasing SID Lys quadratically increased ADG ($P \leq 0.044$) and G:F ($P \leq 0.020$). Increasing SBM linearly increased ADG ($P = 0.039$) and G:F ($P < 0.001$). Increasing NE decreased (linear, $P < 0.10$) ADG due to a reduction in the Lys:NE ratio as NE increased. A SBM × SID Lys interaction ($P = 0.082$) was observed for G:F, where SID Lys increased G:F with increasing SBM due to decreasing the Lys to crude protein (Lys:CP) ratio. In Exp. 2, there were 4,336 pigs (PIC 337 × 1050; initially 10.6 kg) with 34 pigs per pen and 8 pens per treatment. Treatments were arranged in a 2 × 2 × 4 factorial. Eight diets were formulated to various NE, SBM, and SID Lys levels then blended to create the 16 dietary treatments. Main effects included NE (2,425 or 2,676 kcal/kg), SBM (25.5 or 33.5% of the diet), and SID Lys (1.08, 1.20, 1.31, or 1.43%). There was a tendency ($P = 0.063$) for 3-way interaction for ADG

driven by the linear increase ($P < 0.001$) in ADG as SID Lys increased in diets containing 2,627 kcal NE/kg and 33.5% SBM compared to diets at lower SBM and NE with a higher Lys:NE ratio. A 3-way interaction (linear, $P = 0.023$) was observed for G:F. Increasing SBM increased G:F to a greater extent in low energy diets than in high energy diets. Increasing SID Lys resulted in a greater response in high energy diets than in low energy diets. Diets containing low SID Lys and NE but high SBM increased G:F compared with low SID Lys, NE, and SBM also contributing to the interaction. . Data from Exp. 1 predicted results for almost all variables from Exp. 2 within ± 3% of the observed values. In conclusion, a CCD can provide similar estimates of pig growth performance as a factorial arrangement. In addition, both experiments showed the impact of not maintaining Lys:NE ratios when increasing NE and the benefit in G:F when increasing SBM in the diet.

Introduction

The central composite design (CCD) permits the estimation of first- and second-order terms and to quantify the relationship between variables. Box and Wilson (1951) were the first to report this design, which allows the opportunity to explore the relationship between two or more variables with more than three levels. The central, factorial, and axial points represent the experimental domain that establishes the low and high extreme values for treatment variables (Bhattacharya, 2021). The CCD provides a three-dimensional analysis with more uniformity and precision in defining how the response surface behaves around the point of optimum conditions compared to the factorial arrangement (Penneton et al., 1999). Also, it can have the advantage of reducing the number of treatments needed compared to a three-way-factorial experiment to cover the desired ranges for all three factors.

The CCD has been widely used in poultry research since 1960's (Yoshida et al., 1962). Humphrey et al. (2023) recently used a CCD design to evaluate the interaction of branched-chain amino acids in nursery pig diets; however, the CCD model has been less frequently applied in swine compared to poultry research. Although a CCD reduces the number of treatments compared to a full factorial experiment, it still requires a large number of experimental units, often limiting its application in swine research.

Alternatively, a factorial arrangement consists of two or more variables with different levels of each that are compared within every other variable in the experiment. The factorial arrangement requires a greater number of treatments than a CCD to evaluate interactions and main effects (Aaron and Hays, 2001). This treatment arrangement has been widely used in swine nutrition research to investigate the interactions and main effects of two variables of interest. However, when evaluating multiple variables, factorial arrangements can be limited by the number of replications depending on the number of experimental units (pens) available for use.

From 11 to 25 kg, pigs experience a period of rapid growth and increased G:F. Pig growth responses to variable net energy (NE) concentrations have been demonstrated to be inconsistent and relative to the ingredients used in formulation (Oresanya et al., 2007; De Jong et al., 2014; Lunedo et al., 2023). In addition, maintaining the standardized ileal digestible lysine (SID Lys) to calorie (Lys:NE) ratio has been shown to improve growth performance (Marçal et al., 2019), but a recent review also reported that extra growth could be captured when increasing SID Lys over the optimum Lys:NE ratio (Goethals et al., 2024). Soybean meal (SBM) is commonly used in swine diets because it provides an excellent profile of essential and non-essential amino acids (Pope et al., 2023). Previous research has observed variable growth performance responses when feeding up to 40% SBM to pigs from 11 to 25 kg (Cemin et al.,

2020a; Faccin et al., 2023). The response to increasing SID Lys, NE, or SBM individually, or with two of the three variables has been tested, but no research has evaluated the response surface to changing all three variables at the same time.

Therefore, the objective of these trials was to determine the effect of diets differing NE, SBM, and SID Lys on growth performance of late nursery pigs using both a factorial arrangement and a central composite design. We hypothesized that a central composite design can be an alternative to factorial arrangements to test a high number of levels for two or more variables and provide similar results.

Materials and Methods

General

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

Animal and diets

Two studies were conducted at a commercial research-nursery in southwest Minnesota (Leavenworth Livestock Research Facility, Hubbard Feeds, Sleepy Eye, MN). The rooms were mechanically ventilated with totally slatted floors. Each pen (2.44 × 3.81 m^2) was equipped with a 6-hole stainless steel dry self-feeder (SDI, Alexandria, SD) and a stainless-steel bowl waterer for ad libitum access to feed and water. The first experiment was conducted from August 5 to August 25, 2023, and the second experiment was conducted from July 1 to July 22, 2024. All treatment diets were manufactured at the Hubbard Feeds feed mill in Mankato, MN. In both experiments, diets were corn-SBM-based, and soy hulls and soybean oil were added to change the NE content of the diet. The SBM NE value used in diet formulation was assumed to be 2,405

kcal/kg (90% NE of corn; NRC, 2012). Feed grade amino acids and SBM were used to adjust SID Lys and SBM content, respectively, and to maintain SID Thr, Trp, Met, Val, and Ile ratios relative to SID Lys (Tables 1 and 2). Daily feed additions to each pen were accomplished using a computerized feeding system (DryExact Pro; Big Dutchman North America, Holland, MI) to record feed deliveries for individual pens. Pens of pigs were weighed at the beginning and at the end of the studies to determine average daily gain (ADG), average daily feed intake (ADFI), and gain-to-feed ratio (G:F).

Experiment 1 – Central composite design

A total of 4,681 pigs (PIC 337 × 1050; initially 13.0 ± 0.36 kg) were used in a 21-d trial to investigate the interactive effects of NE, SBM, and SID Lys content on growth performance of nursey pigs. Pigs were housed in mixed-sex pens with approximately 35 pigs per pen and assigned in a randomized complete block design to 15 dietary treatments using a circumscribed CCD. The treatment structure consisted of 8 factorial points (treatments 1 to 8), 6 axial points (treatments 9 to 14), and a central point (treatment 15). By design, the central point is repeated at least three times more than the factorial and axial point treatments. Therefore, each factorial and axial point treatment had 7 replications each and the central point had 35 replications. Eight diets were formulated with various levels of NE, SID Lys, and SBM (Table 1) and blended to create the 15 dietary treatments (Table 3). The NE ranged from 2,334 to 2,762 kcal/kg, SBM from 25.5 to 35.9%, and SID Lys from 1.08 to 1.52%.

Experiment 2 – Factorial design

A total of 4,336 pigs (PIC 337 × 1050; initially 10.6 ± 0.32 kg) were used in a 21-d trial to investigate the interactive effects of NE, SBM, and SID Lys content on growth performance of pigs from 11 to 23 kg. Pigs were housed in mixed-sex pens with approximately 34 pigs per pen

with 8 replications per treatment. Dietary treatments were arranged in a 2 × 2 × 4 factorial with 16 dietary treatments. Main effects consisted of NE (2,425 or 2,676 kcal/kg), SBM (25.5 or 33.5% of the diet), and SID Lys (1.08, 1.20, 1.31, or 1.43%). Eight diets were formulated to various NE, SBM, and SID Lys concentrations and blended to create the 16 dietary treatments (Table 2).

Chemical analysis

Feed samples were collected from multiple feeders, blended, subsampled, ground, and analyzed for dry matter, crude protein, crude fiber, ether extract, and ash content (Exp. 1: Midwest Laboratories, Inc., Omaha, NE; Exp. 2: University of Missouri Agricultural Experiment Station Chemical Laboratory, Columbia, MO), and total amino acids profile (Exp. 1: Ajinomoto Health & Nutrition North America, Inc., Eddyville, IA; Exp. 2: University of Missouri Agricultural Experiment Station Chemical Laboratory, Columbia, MO).

Statistical analysis

In both experiments, data were analyzed using R (version 4.1.1 (2021-08-10), R Foundation for Statistical Computing, Vienna, Austria) with pen considered the experimental unit, treatment as fixed effect, and initial weight per pen as the blocking factor. In Exp. 1, data were analyzed as a central composite design of response surface methodology using the RSM function from the RSM package in R software and visualized using perspective. The adjusted R^2 reported indicates the amount of variation in the response explained by the predictor variables. Lack of fit measures the discrepancy between the observed data and the predicted value by the model, meaning that if significant the model does not capture the relationship adequately. Pure error reflects the variation in the response variable that is due to the natural variability in the

experimental process. Some of the variables showed a strong relationship analyzed in the confidence interval between 95% to 90%; therefore, all results were considered significant at $P \leq 0.10$.

In Exp. 2, data were analyzed as a randomized complete block design using the lmer function from the lme4 package in R software. Three-way and 2-way interactions, and main effect of NE, SBM, and SID Lys were analyzed, and the highest order model was reported when statistical significance was observed. Contrast coefficients were used to compare the effect of increasing levels of SID Lys. Differences between treatments were considered significant at $P \leq 0.05$ and marginally significant at $P > 0.05$ and < 0.10.

Model validation

The predictor variables obtained in Exp. 1 (Table 7) were used to predict ADG and G:F using the concentrations of NE, SBM, and SID Lys in Exp. 2 (factorial arrangement). The observed and predicted responses were compared to determine the accuracy of the predicted responses following the procedures by Kerkaert et al. (2021). Treatment 7 from Exp. 1 and treatment 8 from Exp. 2 had the same ingredient composition. Therefore, the intercept term in the equation from the predicted value of treatment 8 was adjusted until the predicted ADG, ADFI, and G:F matched the observed value for this treatment in Exp. 2. Then, the adjusted intercept was used to predict ADG, ADFI, and G:F for the remaining treatments. These values were then compared to the observed values.

Results

General

Overall, pigs in both experiments were healthy and there were minimal removals due to injury, health, or poor performance. In both experiments, chemical analysis of complete diets was consistent with the calculated values used in diet formulation (Table 4 and 5).

Experiment 1 – Central composite design

During the 21-d experimental period, increasing NE decreased ADG (linear, $P < 0.10$), and ADFI (linear, $P < 0.10$), with the response in G:F being quadratic ($P < 0.10$) with G:F increasing as NE increased until approximately 2,600 kcal/kg (Table 6; Figures 1 and 2). When increasing SID Lys, ADG and G:F increased (quadratic, $P < 0.10$) to approximately 1.43% with little benefit thereafter (Figure 3). Increasing SBM increased (linear, $P < 0.10$) ADG and G:F when included at 33.8% of the diet without additional benefits thereafter (Figure 3). There was an interaction (quadratic, $P < 0.10$) observed between SID Lys and SBM on G:F, where increasing SBM in diets with low SID Lys provided a greater response in G:F than when SBM was increased in diets with high SID Lys levels (Figure 4). The CCD results provided linear and quadratic coefficients to develop models to predict ADG, ADFI, and G:F using the significant terms of NE, SBM , and SID Lys as predictor variables (Table 7).

Experiment 2- Factorial design

There was a tendency for a 3-way interaction ($P = 0.063$) in ADG between NE, SBM, and SID Lys (Figure 5; Table 8). Average daily gain increased as SID Lys increased in diets containing 2,627 kcal NE/kg and 33.5% SBM, whereas the response to SID Lys appeared to be quadratic for pigs fed 2,425 kcal NE or 25.5% SBM with 2,676 kcal NE. The main effect of SID

Lys was the only significant (linear, $P < 0.001$) main effect response for ADG, with ADG increasing as SID Lys increased.

There was a main effect of NE and SBM observed ($P < 0.05$) for ADFI. High NE and SBM levels decreased ADFI compared with low NE and SBM. There was also a tendency (linear, $P = 0.085$) for increased ADFI as SID Lys increased.

A 3-way interaction (linear, $P = 0.063$) was observed between NE, SBM, and SID Lys for G:F (Figure 6). Increasing SBM from 25.5 to 33.5% increased G:F to a greater extent in low energy diets than the high energy diets. Increasing SID Lys provided a greater response in the high energy diets than in the low energy diets. The increased G:F in the diet containing 1.08% SID Lys when NE was at 2,425 kcal/kg and SBM at 33.5% as compared to when the same SID Lys and NE was fed with low SBM also contributed to the 3-way interaction.

Model validation

The ADG and G:F predictions, obtained using predictor variables from Exp. 1, were within ± 3% of the observed values in Exp. 2 for all variables and treatments except for treatment 10 (2,676 kcal/kg NE, 25.5% SBM, and 1.20% SID Lys) where ADG and ADFI were underpredicted by 5 and 4%, respectively.

Discussion

Central composite design has been widely used in poultry nutrition research; however, it is not commonly used in swine nutrition research. Central composite design provides first and second-order models and interactions of a large number of variables and their levels with a reduced number of treatments compared to a full factorial model. The factorial and central points used in CCD estimate the interaction and main effects between variables. The axial points are the extreme values that augment the research area, providing the curvature of the responses. The

values obtained at the different points are then used to estimate the intermediate points that were not actually tested, thereby minimizing the number of treatments with a CCD. Although fewer treatments are needed compared to a factorial arrangement, a CCD still requires a high number of experimental units, which is the primary limiting factor for expanding its use in swine research. The main objective of this paper was to validate the usefulness of CCD by comparing the predicted responses with the results obtained with a factorial arrangement. To this end, Exp. 2 was conducted in a factorial arrangement with main effects and diets formulated to approximately the same ranges of SBM (25.5 to 33.5%), NE (2,425 to 2,676 kcal/kg) and SID Lys (1.08 to 1.43%) similar to the range used in Exp.1.

In both experiments, the ADG response was affected by NE, SBM and SID Lys, where SID Lys and its ratio to NE had a large influence on the results in both experiments. The response to SBM was more subtle with a smaller linear main effect in Exp. 1 and as part of a 3-way interaction in Exp. 2.

Increasing SID Lys increased ADG in a quadratic and linear manner in Exp. 1 and 2, respectively. In Exp. 1, no further improvements were observed above 1.43% SID Lys. Menegat et al. (2019) observed that the ideal SID Lys:NE ratio for a 11 to 25 kg pig is approximately 5.27 g/Mcal NE. In Exp. 1, the diets containing 1.43% SID Lys were above the ideal SID Lys:NE ratio (5.61 g/Mcal); therefore, no further improvements in ADG were observed when SID Lys was above 1.43%. In Exp. 2 the highest level of SID Lys used at both NE concentrations were within an ideal Lys:NE ratio for this weight range; therefore, showed a linear response as SID Lys increased. The linear increase in ADG as SID Lys increased in the diet was also observed in other studies when SID Lys increased using a fixed NE level on pigs over 13 kg of BW (Aymerich et al., 2020; Xue et al., 2022).

As previously mentioned, the ideal Lys:NE ratio for a 11 to 25 kg pig is approximately 5.27 g/Mcal NE. Therefore, increasing NE in the diet have to be followed by increasing SID Lys to optimized performance (Marçal et al., 2019). The reduction in ADG observed was due to a reduction in SID Lys:NE ratio as NE increased in Exp. 1. This is because a CCD does not test all possible treatment combinations and most of the high NE concentrations tested were under the ideal Lys:NE ratio. In Exp. 2, at high NE (2,676 kcal/kg) concentrations, the four SID Lys levels tested resulted in wider range of Lys:NE ratios compared to the low NE (2,425 kcal/kg) treatments. Again, the treatment containing 1.43% SID Lys was at ideal SID Lys:NE ratio but the ratio reduced with lower SID Lys, resulting in a linear decrease in ADG. A recent meta-analysis by Goethals et al. (2024) reported that pigs between 11 to 25 kg require from 5.42 to 5.83 g of SID Lys per Mcal of NE to maximized growth performance. This supports that the ratio between dietary NE and SID Lys that should be maintained to support optimum growth performance; however is not always observed at this stage of growth (Lunedo et al., 2023). Pigs typically adjust their feed intake to meet their energy requirement and that is why the SID Lys levels must be adjusted to avoid Lys deficiencies if high energy diets are fed (Chiba et al., 1991).

In Exp.1, increasing SBM resulted in a linear increase in ADG; however, no responses to increasing SBM were observed in Exp. 2. Cemin et al. (2020a) evaluated increasing SBM (27.5 to 37.5% of the diet) in 11 to 25 kg pigs and observed inconsistent ADG responses, with no evidence for differences in three studies, but a linear decreased in ADG as SBM increased in one of the experiments. The small increase in ADG as SBM increased is possibly due to the reduction in the Lys:CP ratio, as SBM provided more non-essential amino acids and N to the diet. The improvements observed in ADG also could be caused by the bioactive compounds in the SBM. A review by White et al. (2024) reported that SBM bioactive compounds, such as

oligosaccharides and isoflavones, may play a beneficial role in the performance on the pigs. The antioxidant effect of isoflavones in pigs is well documented, with the reasons for the beneficial effect of oligosaccharides less clear, but the influence on pig growth performance could be related to the level of these compounds increasing as SBM is increased in the diet.

In both experiments, ADFI decreased as dietary NE increased. Even though Lunedo et al. (2023) indicated that increasing NE did not affect ADFI of pigs from 7 to 20 kg of BW, other studies have indicated that feed intake decreases with increasing NE in 11 to 15 kg pigs (Beaulieu et al., 2006; Mendoza and Van Heugten, 2014). This indicates that pigs will adjust their intake as dietary NE increases to more closely reach their daily caloric requirement (Chiba et al., 1991).

Feed intake was decreased when feeding 33.5% SBM compared to 25.5% in Exp. 2, but there were no differences observed in Exp. 1. Cemin et al. (2020a) observed a linear reduction in ADFI as SBM increased from 27.5 to 37.5% in two of four studies. Faccin et al. (2023) also observed a linear reduction in ADFI in two studies when feeding 25 to 40% SBM to 11 to 28 kg pigs. The results herein, as well as those of Cemin et al. (2020a) and Faccin et al. (2023), might suggest that very high levels of SBM in the diet decrease ADFI possibly due to palatability. Heo et al., (2013) suggested that high CP levels fed in nursery diets increased the fermentation of protein substrates in the large intestine which can result with the production of toxic compounds such as ammonia and amines. The reasons why the reduction in ADFI was observed in Exp. 2 and not in Exp. 1 are unclear, but it could be attributed to a reduction in palatability and/or the amount of bioactive compounds present as SBM increased.

Increasing SID Lys, linearly increased ADFI. Kendall et al. (2008) conducted five studies evaluating SID Lys from 1.05 to 1.50% of the diet in pigs from 11 to 27 kg and did not observed

differences in ADFI as SID Lys increased. This may suggest that ADFI response observed in our experiments is not related to increasing SID Lys but to other components of the diets.

In Exp. 1, an interaction between SID Lys and SBM was observed for G:F, with G:F increasing to a greater extent when SBM levels increased in the diet with low SID Lys than in diets with high SID Lys. This response is possibly caused by the other essential amino acids, non-essential amino acids, and N provided as SBM content increased in the diet (Pope et al., 2023). In Exp. 2, there was a 3-way interaction between the NE, SBM, and SID Lys levels, driven by increased G:F in the diet containing 1.08% SID Lys when NE was at 2,425 kcal/kg and SBM at 33.5% as compared to when the same SID Lys and NE were fed with low SBM. Most of the essential amino acids are commercially available to be added in a feed-grade form in the diet; however, the non-essential amino acids can become limiting when the SID Lys to crude protein content becomes too high to provide adequate N for non-essential amino acid synthesis. Additionally, although diets were formulated to be above the His:Lys ratio suggested by Cemin et al. (2018), SID His:Lys and other essential amino acids increased as SBM was added to the diets. Therefore, when extra amino acids and protein from SBM were provided, the benefits in pig performance were observed. Similar effects were observed when increasing the CP level of the diet fed to nursery pigs (Kim et al., 2011; Limbach et al., 2021; Correia et al., 2023). Also, Silva et al. (2020) observed greater N retention in carcasses and viscera when more N and non-essential amino acids are fed.

The differences in Lys:NE ratios also may explain part of the 3-way interaction observed in Exp. 2. When comparing the treatments at the same Lys:NE ratio (2,425 kcal/kg NE), the treatment containing high SBM provided more non-essential amino acids resulting in greater G:F compared to the pigs fed diets with lower SBM. The same improvements in G:F were not found

as SBM increased in the high NE diets (2,676 kcal/kg). The reason is not totally clear; however, these diets would have had lower SID Lys:NE ratios than pigs fed the low NE diets because diets were formulated to a constant SID Lys percentage. Another possibility to consider is that the NE value used for SBM in our diet formulation was 2,405 kcal/kg, equivalent to 90% of the NE value of corn (NRC, 2012). Based on caloric efficiency and digestibility studies, it was observed that the NE content of SBM is greater than the current values estimated by NRC (2012; Rojas and Stein, 2013; Li et al., 2017; Cemin et al., 2020b). Thus, the response observed in G:F could be partially attributed to more NE contributed to the diet by SBM.

The validation of the model generated from the CCD showed the ability of it to predict the responses obtained with the factorial arrangement within ± 3% of the observed values in almost all comparisons. The predictions of treatment 10 were an exception where the model underpredicted ADG and ADFI by 5% and 4%, respectively. The reason for the discrepancy is not entirely known but appears to be because the negative effect of dietary NE on feed intake was less in the values observed in Exp. 2 than the predicted ones, with the greatest discrepancy in treatment 10. Nevertheless, these results demonstrated that CCD can be used to accurately predict changes in growth performance of pigs in response to different dietary components. Therefore, if facility constraints allow for adequate replications, CCD allows a high number of variables and levels to be tested simultaneously.

In summary, the model obtained with the CCD provided accurate estimates for ADG and G:F when applied to similar nutrient levels from the factorial arrangement. In addition, the growth performance results demonstrated the importance of maintaining Lys:NE ratios to improve performance and the impact of N and other non-essential amino acids (Lys:CP ratio)

contributed by SBM to increase G:F. We therefore conclude that CCD can be effectively used in swine research to predict growth performance responses to different nutrient levels.

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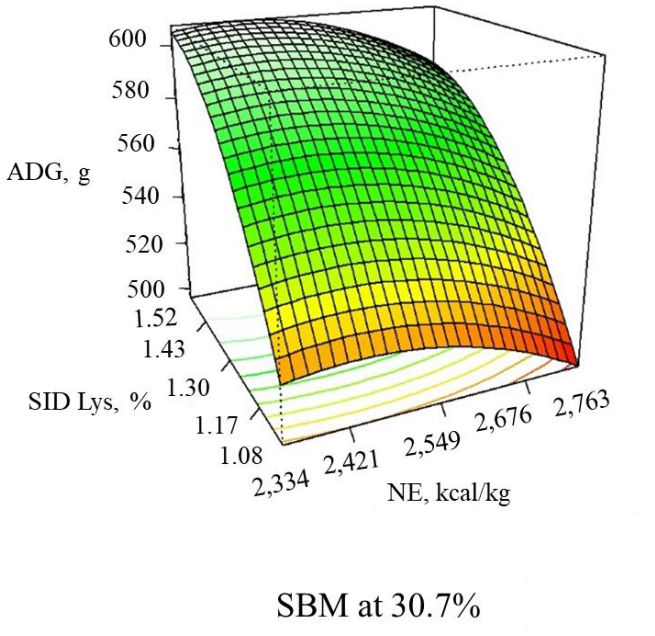

Figure 5.1. Response surface plot of NE (Linear, *P* = 0.052) and SID Lys (Quadratic, *P* = 0.044) on ADG with SBM held at the midpoint (30.7%) in pigs from 11 to 25 kg. Adj. R^2= 0.355

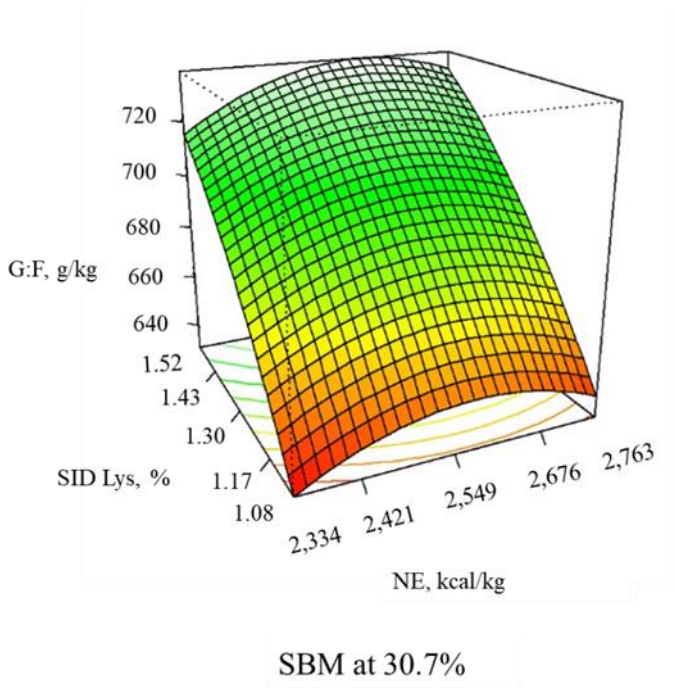

Figure 5.2. Response surface plot of NE (Quadratic, $P = 0.005$) and SID Lys (Lys × SBM, $P = 0.082$) on G:F with SBM held at the midpoint (30.7%) in pigs from 11 to 25 kg. Adj. $R^2 = 0.655$

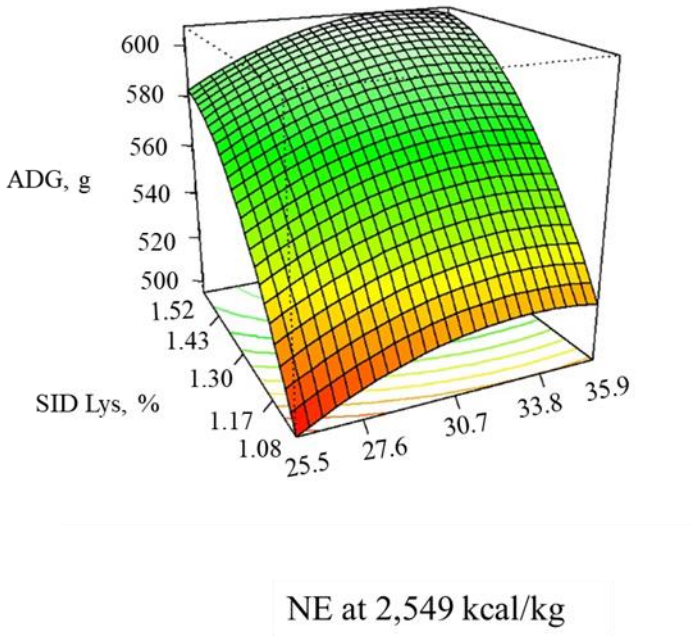

Figure 5.3. Response surface plot of SBM (Linear, $P = 0.039$) and SID Lys (Quadratic, $P < 0.044$) on ADG with NE held at the midpoint (2,549 kcal/kg) in pigs from 11 to 25 kg. Adj. $R^2 = 0.355$

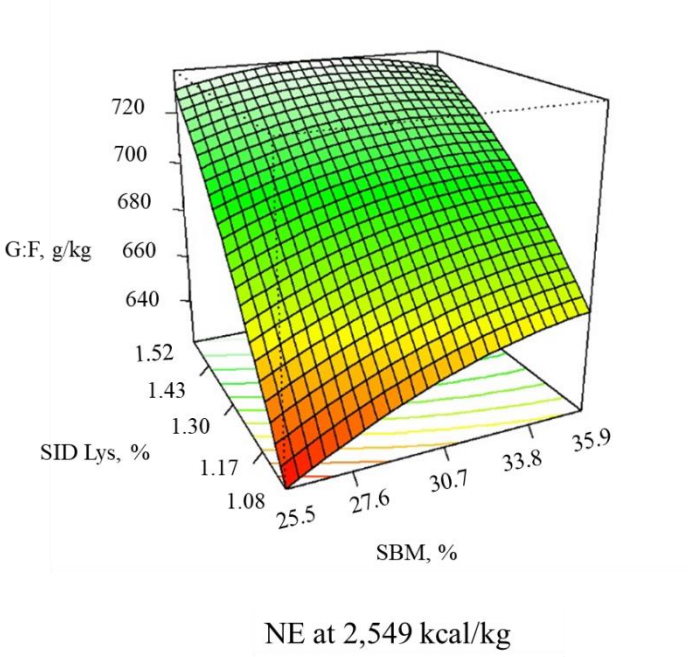

Figure 5.4. Response surface plot of SBM (Lys × SBM, *P* = 0.082) and SID Lys (Lys × SBM, *P* = 0.082) on G:F with NE held at the midpoint (2,549 kcal/kg) in pigs from 11 to 25 kg. Adj. R^2= 0.655

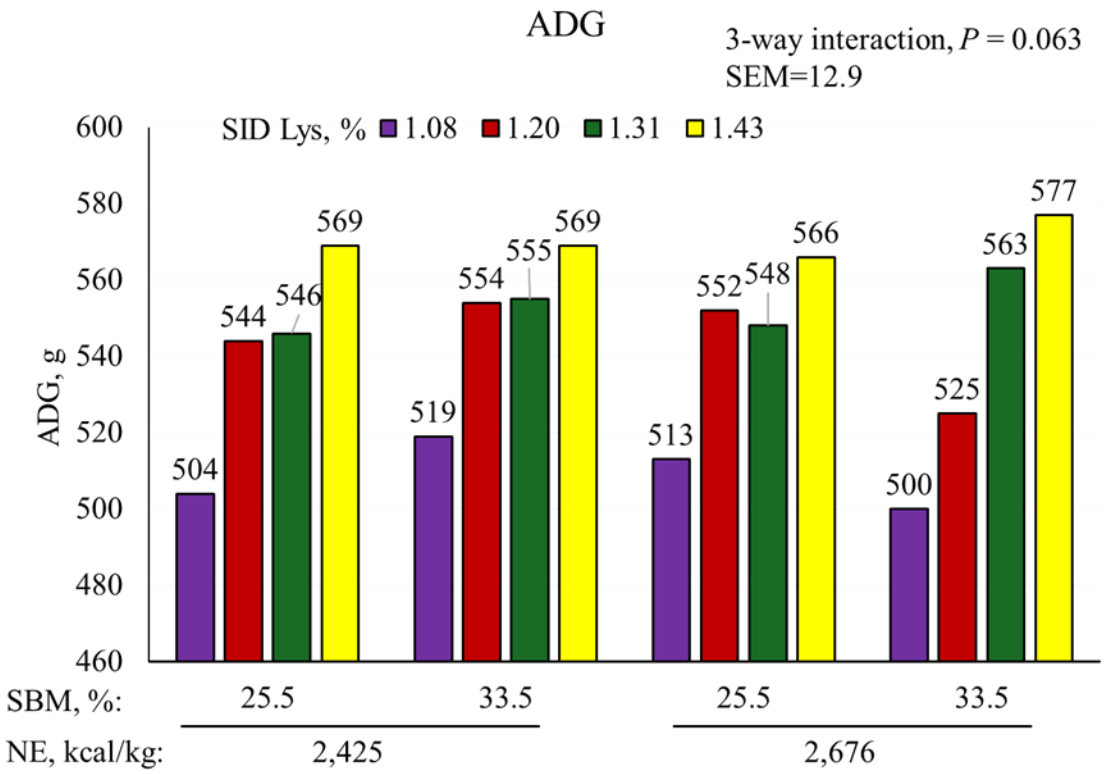

Figure 5.5. Interactive effects of NE, SBM, and SID Lys on ADG of pigs from 11 to 23 kg.

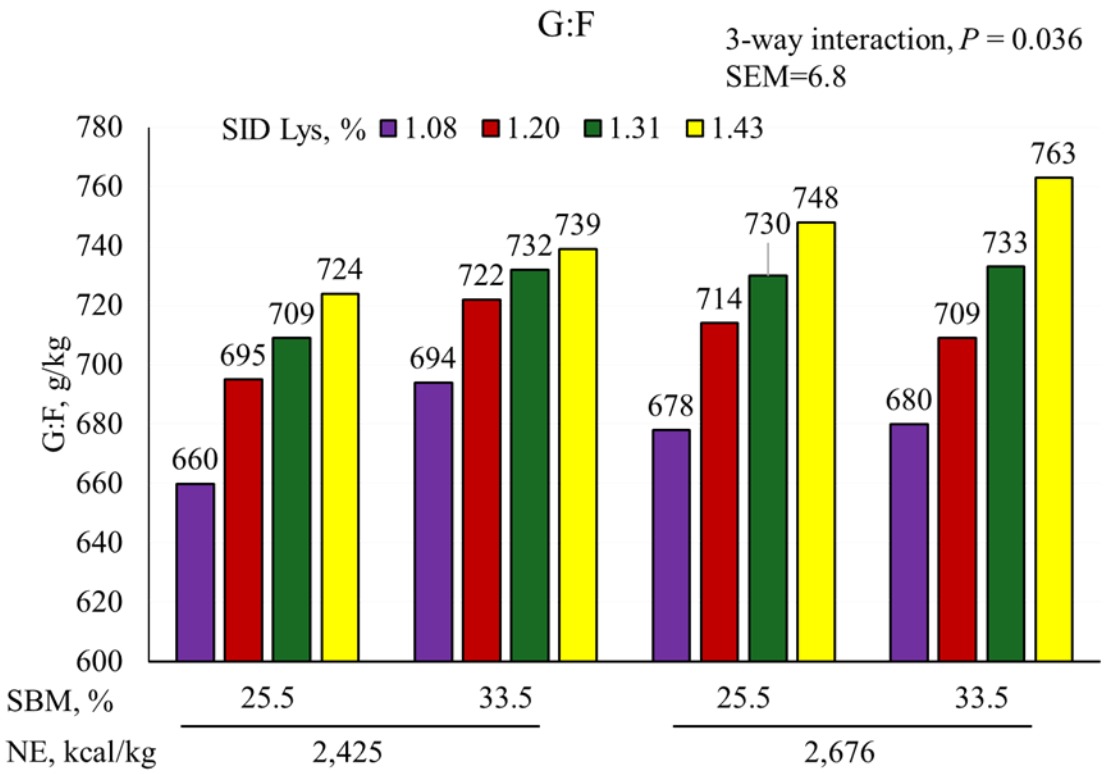

Figure 5.6. Interactive effects of NE, SBM, and SID Lys on G:F of pigs from 11 to 23 kg.

Table 5.1. Composition of experimental diets, Exp. 1 (as-fed basis)[1,2]

Item	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5	Diet 6	Diet 7	Diet 8
Ingredients, %								
Corn	56.48	49.15	58.85	51.24	65.18	55.58	66.79	56.87
Soybean meal, 47.7% CP	25.50	35.57	25.50	35.57	25.50	25.50	25.50	35.57
Soybean hulls	13.30	11.58	12.72	10.94	---	---	---	---
Soybean oil	---	---	---	---	4.29	4.87	4.48	5.08
Limestone	0.46	0.47	0.48	0.49	0.65	0.66	0.66	0.64
Monocalcium P, 21% P	0.94	0.86	0.94	0.85	0.95	0.95	0.95	0.86
Salt	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
L-Lys-HCl	0.87	0.56	0.31	---	0.92	0.36	0.36	0.04
DL-Met	0.42	0.32	0.14	0.05	0.42	0.15	0.15	0.06
L-Trp	0.13	0.07	0.03	---	0.13	0.04	0.04	---
L-Thr	0.44	0.30	0.15	0.01	0.46	0.17	0.17	0.03
L-Val	0.33	0.16	0.02	---	0.35	0.03	0.03	---
L-Ile	0.28	0.11	0.01	---	0.30	0.02	0.02	---
Vitamin-trace mineral premix[2]	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Phytase[3]	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
TOTAL	100	100	100	100	100	100	100	100
Calculated analysis								
Standardized ileal digestible (SID) amino acids								
Lys, %	1.52	1.52	1.08	1.08	1.52	1.52	1.08	1.08
Ile:Lys	60	60	60	74	60	60	60	73
Leu:Lys	87	103	124	146	87	102	124	144
Met:Lys	44	41	37	32	44	41	38	33
Met and Cys:Lys	60	60	60	60	60	60	60	60
Thr:Lys	65	65	65	65	65	65	65	65
Trp:Lys	21	21	21	23	21	21	21	23
Val:Lys	70	70	70	84	70	70	70	83
His:Lys	27	33	39	47	27	32	38	46

Total Lys, %	1.68	1.70	1.24	1.26	1.65	1.67	1.21	1.23
NE, kcal/kg	2,334	2,334	2,334	2,334	2,762	2,762	2,762	2,762
SID Lys:NE, g/Mcal	6.51	6.51	4.63	4.63	5.50	5.50	3.91	3.91
CP, %	19.4	22.7	18.2	21.6	18.5	21.9	17.3	20.8
Ca, %	0.55	0.57	0.55	0.58	0.55	0.58	0.56	0.58
Available P, %	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46

[1]Fed from approximately 13 to 25 kg.

[2] Vitamin and trace mineral premix with added Alltech Sel-Plex 600 (Alltech, Nicholasville, KY) at same amount in all the diets.

[3]Quantum Blue 5G (AB Vista, Marlborough, UK) was included at 680 FTU/kg providing an estimated release of 0.16% available P.

Table 5.2. Composition of experimental diets, Exp. 2 (as-fed basis)[1,2,3]

Item	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5	Diet 6	Diet 7	Diet 8
Ingredients, %								
Corn	60.43	57.77	55.02	52.83	65.16	63.34	57.48	56.03
Soybean meal, 47.7% CP	25.49	25.52	33.53	33.56	25.50	25.48	33.57	33.55
Soybean hulls	9.80	11.00	7.80	8.75	2.30	2.90	2.00	2.40
Soybean oil	1.00	1.05	0.85	0.90	3.60	3.45	4.05	3.90
Limestone	0.70	0.68	0.77	0.75	0.81	0.79	0.85	0.84
Monocalcium P, 21% P	1.03	1.03	1.00	1.00	1.03	1.03	1.00	1.00
Salt	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
L-Lys-HCl	0.33	0.77	0.08	0.52	0.35	0.80	0.10	0.55
DL-Met	0.15	0.36	0.07	0.29	0.15	0.36	0.08	0.30
L-Trp	0.04	0.11	---	0.07	0.05	0.11	---	0.07
L-Thr	0.15	0.38	0.04	0.27	0.15	0.39	0.04	0.28
L-Val	0.05	0.30	---	0.16	0.06	0.31	---	0.17
L-Ile	---	0.22	---	0.08	0.01	0.23	---	0.09
Vitamin-trace mineralpremix[4]	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Phytase[5]	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
TOTAL	100	100	100	100	100	100	100	100
Calculated analysis								
Standardized ileal digestible (SID) amino acids								
Lys, %	1.08	1.43	1.08	1.43	1.08	1.43	1.08	1.43
Ile:Lys	60	60	73	60	60	60	72	60
Leu:Lys	127	95	145	106	127	95	145	108
Met:Lys	37	42	33	40	37	42	33	40
Met and Cys:Lys	60	60	60	60	60	60	60	60
Thr:Lys	65	65	65	65	65	65	65	65
Trp:Lys	21	21	21	21	21	21	21	21
Val:Lys	71	70	78	70	70	70	78	70
His:Lys	40	30	47	35	40	30	47	35
Total Lys, %	1.23	1.58	1.25	1.59	1.21	1.56	1.23	1.58

NE, kcal/kg	2,425	2,425	2,425	2,425	2,676	2,676	2,676	2,676
SID Lys:NE, g/Mcal	4.45	5.88	4.45	5.89	4.03	5.34	4.03	5.34
CP, %	18.7	19.7	21.5	22.3	18.4	19.4	21.1	22.0
Ca, %	0.62	0.61	0.65	0.65	0.62	0.61	0.65	0.65
Available P, %	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46

[1] Fed from approximately 10 to 23 kg.

[2] Diets 1 to 8 were fed as is to accomplish the nutrient requirements for treatments 1, 4, 5, 8, 9, 12, 13, and 16, respectively.

[3] The following treatments were accomplish by the following blends: treatment 2 (Diet 1 [75%] and 4 [25%]); treatment 3 (Diet 1 [25%] and 4 [75%]); treatment 6 (Diet 5 [75%] and 8 [25%]); treatment 7 (Diet 5 [25%] and 8 [75%]); treatment 10 (Diet 9 [75%] and 12 [25%]); treatment 11 (Diet 9 [25%] and 12 [75%]); treatment 14 (Diet 13 [75%] and 16 [25%]); treatment 15 (Diet 13 [25%] and 16 [75%]).

[4] Vitamin and trace mineral premix with added Alltech Sel-Plex 600 (Alltech, Nicholasville, KY) at same amount in all the diets.

[5] Quantum Blue 5G (AB Vista, Marlborough, UK) was included at 680 FTU/kg providing an estimated release of 0.16% available P.

Table 5.3 . Nutrient composition and diet blend proportion used to meet the nutrient levels of the fifteen dietary treatments of Exp. 1.

	Nutrient level			Diet blend, %[1]							
Treatment	NE, kcal/kg	SID Lys, %	SBM, %	1	2	3	4	5	6	7	8
1	2,421	1.17	27.6	---	---	80	---	---	20	---	---
2	2,676	1.17	27.6	---	20	---	---	---	---	80	---
3	2,421	1.43	27.6	80	---	---	---	---	---	---	20
4	2,676	1.43	27.6	---	---	---	20	80	---	---	---
5	2,421	1.17	33.8	---	---	---	80	20	---	---	---
6	2,676	1.17	33.8	20	---	---	---	---	---	---	80
7	2,421	1.43	33.8	---	80	---	---	---	---	20	---
8	2,676	1.43	33.8	---	---	20	---	---	80	---	---
9	2,334	1.30	30.7	---	50	50	---	---	---	---	---
10	2,763	1.30	30.7	---	---	---	---	---	50	50	---
11	2,549	1.08	30.7	---	---	50	---	---	---	---	50
12	2,549	1.52	30.7	50	---	---	---	---	50	---	---
13	2,549	1.30	25.5	50	---	---	---	---	---	50	---
14	2,549	1.30	35.9	---	---	---	50	---	50	---	---
15	2,549	1.30	30.7	---	---	50	---	---	50	---	---

[1] Percentage of the eight diets manufacture to meet the requirement of the fifteen dietary treatments.

Table 5.4. Chemical analysis of Exp. 1 diets (as fed-basis)[1]

	Item		
Diet	CP, %	Ether extract, %	Total Lys, %
1	17.8	3.16	1.36
2	19.7	5.57	1.28
3	19.0	3.41	1.53
4	18.9	5.52	1.57
5	19.6	3.14	1.29
6	20.8	6.13	1.37
7	20.0	3.40	1.53
8	20.7	6.06	1.51
9	18.6	2.36	1.43
10	18.1	7.04	1.38
11	20.6	5.21	1.24
12	19.9	5.35	1.64
13	17.8	4.96	1.38
14	19.9	4.62	1.35
15	19.8	4.63	1.40

[1] Values represent means from 4 composite samples. For each treatment, samples were collected from multiple feeders, blended, subsampled, ground, and analyzed (Midwest Laboratories, Inc., Omaha, NE; Ajinomoto Health & Nutrition North America, Inc., Eddyville, IA).

Table 5.5. Chemical analysis of Exp. 2 diets (as fed-basis)[1]

	Item		
Diet	CP, %	Ether extract, %	Total Lys, %
1	17.4	2.5	1.30
2	18.3	2.7	1.44
3	18.4	2.7	1.53
4	19.2	2.9	1.60
5	20.9	2.2	1.31
6	20.7	2.4	1.48
7	20.8	2.5	1.60
8	21.1	2.5	1.68
9	17.6	5.4	1.33
10	18.3	5.8	1.44
11	18.1	5.7	1.43
12	18.6	6.2	1.65
13	19.5	4.0	1.23
14	20.3	3.5	1.48
15	20.2	3.7	1.48
16	21.3	4.3	1.64

[1] Values represent means from 4 composite samples. For each treatment, samples were collected from multiple feeders, blended, subsampled, ground, and analyzed (University of Missouri Agricultural Experiment Station Chemical Laboratory, Columbia, MO).

Table 5.6. Performance of nursery pigs fed five levels of net energy (NE), standardized ileal digestible lysine (SID Lys), and soybean meal (SBM) content using a central composite design (Exp. 1)[1]

	Nutrient level[2]			Growth performance response			
Treatment	NE[3]	SBM[4]	Lys[5]	Final BW, kg	ADG, g	ADFI, g	G:F, g/kg
1	2,420	27.6	1.17	23.6	542	828	654
2	2,677	27.6	1.17	23.0	516	789	653
3	2,420	27.6	1.43	24.4	585	819	715
4	2,677	27.6	1.43	24.4	579	806	719
5	2,420	33.8	1.17	23.9	547	822	666
6	2,677	33.8	1.17	23.6	534	783	682
7	2,420	33.8	1.43	24.8	594	831	714
8	2,677	33.8	1.43	25.1	604	827	731
9	2,334	30.7	1.30	24.7	588	863	682
10	2,762	30.7	1.30	24.1	558	809	689
11	2,549	30.7	1.08	23.5	526	809	650
12	2,549	30.7	1.52	24.7	604	827	731
13	2,549	25.5	1.30	23.9	562	823	683
14	2,549	35.9	1.30	24.7	583	831	701
15	2,549	30.7	1.30	24.4	579	826	701
SEM				0.77	12.2	20.2	6.6
R^2				0.059	0.385	0.073	0.670
Adjusted R^2				0.014	0.355	0.029	0.655
P[6]							
Interactions							
NE × Lys				NS	NS	NS	NS
NE × SBM				NS	NS	NS	NS
Lys × SBM				NS	NS	NS	0.082
Quadratic							
NE				NS	NS	NS	0.005

Lys	NS	0.044	NS	0.020
SBM	NS	NS	NS	NS
Linear				
NE	0.546	0.052	0.011	0.047
Lys	0.017	< 0.001	0.210	< 0.001
SBM	0.241	0.039	0.639	< 0.001
Lack of fit[7]	0.999	0.798	0.923	0.822
Pure error[8]	4.41	0.07	0.12	0.04

[1] A total of 4,681 pigs (PIC 337 × 1050, initially 13.0 ± 0.36 kg) were used in a 21-d experiment using central composite design of response surface methodology. Approximately 35 pigs per pen were used and assigned to 1 of 15 treatments in a completely randomized block design.

[2] Each of the 3 factors NE, SID Lys, and SBM content were tested in five different levels (-α, -1, 0, +1, and +α) calculated based on the central values (0) selected for this period.

[3] Net energy levels (kcal/kg): -α=2,334; -1=2,420; 0=2,549; +1=2,677; and +α=2,762.

[4] SID Lys levels (%): -α=1.08; -1=1.17; 0=1.30; +1=1.43; and +α=1.52.

[5] Soybean meal (%): -α=25.5; -1=27.6; 0=30.7; +1=33.8; and +α=35.9.

[6] Results were considered significant at a *P* value ≤ 0.10. NS = Non-significant.

[7] Indicates how well the model fits the data. The higher the lack of fit p-value indicates a better fitting model for the responses analyzed.

[8] Standard deviation of replicates at the center points. Calculated as √MSE.

Table 5.7. Regression equations for prediction of nursery pig ADG, ADFI, and G:F in response to net energy (NE), SID lysine (Lys), and soybean meal (SBM) content

Response variable	Regression equation[1]	*P*	Adjusted R^2
ADG, kg	=0.579392 - (0.0063389 × NE) + (0.0260796 × Lys) + (0.0067428 × SBM) - (0.0065721 × Lys²)	< 0.001	0.355
ADFI, kg	=0.8210353 - (0.0136864 × NE) + (0.0066549 × Lys) + (0.0024825 × SBM)	0.040	0.040
G:F	=0.7013215 + (0.0035198 × NE) + (0.0264389 × Lys) + (0.0060863 × SBM) - (0.0048012 × NE²) - (0.0031838 × Lys²) - (0.0034413 × Lys × SBM)	< 0.001	0.654

[1] Equations from central composite design analysis are expressed relative to user input. Thus, dietary components in the equations need to be included in the equation as follow: NE= [User NE (kcal/kg) – 2,548.5] ÷ 214; SBM= [User SBM (%) – 30.7] ÷ 5.2; SID Lys= [User SID Lys (%) – 1.3] ÷ 0.22

Table 5.8. Interactive and main effects of feeding pigs two levels of net energy (NE) and soybean meal (SBM) with four levels of SID lysine (Lys) on growth performance (Exp. 2)[1]

Nutrient level				Growth performance response			
Treatment	NE	SBM	Lys	BW, kg	ADG, g	ADFI, g	G:F, g/kg
1	2,425	25.5	1.08	21.3	504	764	660
2	2,425	25.5	1.20	22.0	544	784	695
3	2,425	25.5	1.31	22.1	546	771	709
4	2,425	25.5	1.43	22.6	569	786	724
5	2,425	33.5	1.08	21.6	519	749	694
6	2,425	33.5	1.20	22.3	554	768	722
7	2,425	33.5	1.31	22.3	555	758	732
8	2,425	33.5	1.43	22.6	569	771	739
9	2,676	25.5	1.08	21.4	513	757	678
10	2,676	25.5	1.20	22.2	552	773	714
11	2,676	25.5	1.31	22.1	548	751	730
12	2,676	25.5	1.43	22.5	566	757	748
13	2,676	33.5	1.08	21.1	500	735	680
14	2,676	33.5	1.20	21.9	525	741	709
15	2,676	33.5	1.31	22.5	563	768	733
16	2,676	33.5	1.43	22.8	577	757	763
SEM				0.52	12.9	19.2	6.8
P[2]							
3-way interaction[3]							
Linear SID Lys × SBM × NE				0.174	0.063	0.298	0.036
2-way interactions[3]							
NE × SBM				0.604	0.230	0.645	<0.001
Linear SID Lys × NE				0.495	0.360	0.718	0.006
Linear SID Lys × SBM				0.529	0.419	0.250	0.724
Main effects							
NE				0.766	0.651	0.018	0.001

SBM	0.499	0.584	0.043	<0.001
SID Lys, linear	< 0.001	<0.001	0.085	<0.001
SID Lys, quadratic	0.172	0.068	0.407	0.015

[1] A total of 4,336 pigs (PIC 337 × 1050, initially 10.6 ± 0.32 kg) were used in a 21-d experiment. Approximately 34 pigs per pen were used and assigned to 1 of 16 treatments in a completely randomized block design.

[2] Results were considered significant at a $P \leq 0.05$ and marginally significant at $0.05 < P < 0.10$. NS= non-significant.

[3] Quadratic terms of SID Lys with the two other factors were not significant ($P > 0.10$)

Table 5.9. Predicted values of average daily gain (ADG), average daily feed intake (ADFI), and gain-to-feed ratio (G:F) using the nutrient levels from Exp. 2 with the estimators obtained in Exp. 1.

	Observed[1]			Predicted[2]			%[3]		
Treatment	ADG	ADFI	G:F	ADG	ADFI	G:F	ADG	ADFI	G:F
1	504	764	660	513	757	683	98	101	97
2	544	784	695	532	760	702	102	103	99
3	546	771	709	547	764	718	100	101	99
4	569	786	724	559	767	733	102	102	99
5	519	749	694	523	760	698	99	99	99
6	554	768	722	543	764	714	102	101	101
7	555	758	732	557	767	727	100	99	101
8	569	771	739	569	771	739	100	100	100
9	513	757	678	505	741	687	102	102	99
10	552	773	714	525	744	706	105	104	101
11	548	751	730	539	747	722	102	101	101
12	566	757	748	551	751	737	103	101	101
13	500	735	680	516	744	702	97	99	97
14	525	741	709	535	748	718	98	99	99
15	563	768	733	550	751	731	102	102	100
16	577	757	763	562	755	743	103	100	103

[1] Mean values observed in Exp. 2

[2] Values were obtained using the estimators in table 6 and the nutrient levels of Exp. 2. Treatment 7 and 8 from Exp. 1 and 2, respectively, had the same ingredient composition. Therefore, the intercept term in the equation from the predicted value of treatment 8 was adjusted until the predicted ADG and G:F matched the observed value in Exp. 2. Then, the adjusted term of each response was used to predict the remaining treatments.

[3] (Observed ÷ Predicted) × 100.