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Non Ruminant Nutrition

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Phase-feeding strategies based on lysine specifications for grow-finish pigs[1]

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Abstract

Four experiments were conducted using 1,100 to 1,188 pigs each (PIC 359 × 1,050) from ~27 to 127 kg BW to evaluate phase-feeding strategies based on Lys specifications and number of dietary phases for grow-finish pigs. Different phase-feeding strategies were used in each experiment with treatments consisting of a combination of 3 Lys specifications at 96%, 98%, or 100% of estimated requirement for growth rate and 4 phase-feeding strategies with 1, 2, 3, or 4 dietary phases. A single-phase-feeding strategy reduced ($P < 0.05$) overall growth performance, live BW, and HCW whether Lys specifications were at 98% or 100% of estimated requirements compared with multi-phase-feeding strategies. Lysine specifications at 96% of estimated requirements in a 4-phase-feeding strategy reduced ($P < 0.05$) overall growth performance compared with feeding strategies with Lys at 100% of estimated requirements, unless Lys specifications were increased to 100% of estimated requirements in the late finishing phase. Lysine specifications at 98% or 100% of estimated requirements in a 2-, 3- or 4-phase feeding strategy led to similar ($P < 0.05$) overall growth rate, live BW, and HCW of grow-finish pigs. Pigs fed 1, 2, or 3-phase feeding strategies or feeding strategies with Lys below the requirements in early grow finish had improved growth performance driven by improved feed efficiency in the period following low Lys levels, indicating the occurrence of compensatory growth. For carcass characteristics, there was no evidence ($P > 0.10$) for differences in carcass yield, back fat, loin depth, or lean percentage across feeding strategies in any of the experiments. In conclusion, phase-feeding strategies provide performance advantages over feeding a single dietary phase throughout the grow-finish period. Simplification of feeding strategies from 4 to 3 or 2 dietary phases with Lys specifications at 98% to 100% of estimated requirements for growth rate does not compromise overall growth performance and carcass characteristics of grow-finish pigs from 27 to 127 kg BW. Although, using feeding programs with fewer dietary phases and Lys set slightly below the requirements can compromise growth performance if initial BW and feed intake in the grow-finish period are lower than expected.

Key words: carcass, compensatory growth, feeding program, performance, protein, swine

Introduction

Phase-feeding strategies have been widely used to closely meet the nutrient requirements of grow-finish pigs (Han et al., 2000).

The core component of developing phase-feeding strategies lies on determining dietary Lys specifications as Lys is the first limiting AA in most swine diets and determines optimal growth and lean deposition (Main et al., 2008). Dietary Lys concentration decreases over the grow-finish period with phase feeding used as an attempt to meet the biological requirements of pigs as their ability to consume feed exceeds their capacity for protein deposition (NRC, 2012). However, in practice, the variation in weight, growth rate, and feed intake within a population prevents accurate estimation and delivery of optimal Lys concentration for growth on an individual basis even with meticulously designed phase-feeding strategies (Pomar and Remus, 2019).

Phase-feeding strategies with fewer dietary phases typically provide at or below Lys requirements initially and provide adequate or excess Lys levels later in the phase. Previous studies suggest simplification of phase-feeding strategies to fewer dietary phases can lead to optimal grow-finish performance and carcass characteristics and, from an economic and environmental standpoint, can minimize dietary protein input and nitrogen excretion in early grow finish (O'Connell et al., 2005; Moore et al., 2012). Simplification of phase-feeding strategies may be an opportunity to exploit compensatory growth. There is evidence of compensatory growth induced by Lys restriction in nursery pigs (Totafurno et al., 2017; Nemechek et al., 2018) as well as grow-finish pigs (reviewed by Menegat et al., 2019). Pigs exhibiting compensatory growth have improvements in feed efficiency and Lys utilization efficiency, which may be beneficial for overall swine production efficiency (Fabian et al., 2004; Reynolds and O'Doherty, 2006).

Therefore, the objective of this study was to evaluate whether simplification of phase-feeding strategies using different Lys specifications for growth rate is possible without compromising overall performance and carcass characteristics of grow-finish pigs.

Materials And Methods

The Kansas State University Institutional Care and Use Committee approved the protocol used in the experiments. A series of 4 experiments were conducted to evaluate phase-feeding strategies based on Lys specifications and the number of dietary phases in the grow-finish period.

Animals and Dietary Treatments

Experiments were conducted at a commercial research facility in southwestern Minnesota. The barns used in the experiments were identical, naturally ventilated, and double curtain sided. In each experiment, a total of 1,100 to 1,188 pigs (359 × 1,050, Genus PIC, Hendersonville, TN) were housed in 44 pens with 25 to 27 mixed-gender pigs per pen from approximately 27 to 127 kg BW and ~120 d. Pens (5.5 × 3.0 m) had completely slatted floors and were equipped with a four-hole stainless steel dry self-feeder and a cup waterer. Pigs were allowed ad libitum access to feed and water. Feed additions were accomplished and recorded by a computerized-feeding system (FeedPro, Feedlogic Corp., Wilmar, MN).

In each experiment, pens of pigs were blocked by BW and randomly assigned to 1 of 4 treatments arranged in a randomized complete block design with 11 replicates per treatment. Treatments consisted of feeding strategies based on Lys specifications (96%, 98%, and 100% of estimated Lys requirements for growth rate) and the number of dietary phases (1, 2, 3, or 4 dietary phases) in the grow-finish period. The Lys specifications at 96%, 98%, and 100% of estimated requirements for growth rate were derived from the genetic supplier's Lys requirement prediction equation based on commercial experiments: standardized ileal digestible Lys, g/Mcal NE = 0.000056 × (BW, kg × 2.2046)^2 – 0.02844 × (BW, kg × 2.2046) + 6.6391 (Genus PIC; Gonçalves et al., 2017). Lysine levels were set at the midpoint of the BW range within a dietary phase. The number of dietary phases were 1, 2, 3, or 4 dietary phases, termed 1-phase, 2-phase, 3-phase, and 4-phase, respectively. An overview of weight range, duration, and Lys:calorie ratio used in each experiment are outlined in Table 1.

In experiment 1, treatments consisted of: a 2-phase-feeding strategy with Lys specifications at 100% of estimated requirements; a 4-phase-feeding strategy with Lys specifications at 100% of estimated requirements; a 4-phasefeeding strategy with Lys specifications at 96% of estimated requirements; and a 4-phase feeding strategy with Lys specifications at 96% of estimated requirements in growing (27 to 72 kg BW) and at 100% of estimated requirements in finishing (72 to 127 kg BW). In experiment 2, treatments consisted of 1-, 2-. 3-, or 4-phase-feeding strategies with Lys specifications at 100% of estimated requirements. In experiment 3, treatments consisted of 1-, 2-. 3-, or 4-phase feeding strategies with Lys specifications at 98% of estimated requirements. In experiment 4, treatments consisted of: a 2-phase feeding strategy with Lys specifications at 98% of estimated requirements; a 2-phase-feeding strategy with Lys specifications at 98% of estimated requirements in growing finishing (27 to 100 kg BW) and at 100% of estimated requirements in late finishing (100 to 127 kg BW); a 3-phase feeding strategy with Lys specifications at 98% of estimated requirements; and a 4-phase-feeding strategy with Lys specifications at 98% of estimated requirements.

In all experiments, diets were based on corn, distillers dried grains with solubles, and soybean meal (Tables 2–5). Distillers dried grains with solubles were withdrawn from the last dietary phase except for 1-phase-feeding strategies and all feeding strategies in experiment 2. The sources of corn, distillers dried grains with solubles, and soybean meal used in the experiments have been regularly sampled and tested for AA content. These values were used in diet formulation and standardized ileal digestible AA coefficients were derived from NRC (2012). Lysine levels in experimental diets were achieved by changing the amount of soybean meal. All other nutrient requirements met or exceeded the NRC (2012) recommendations in all dietary phases. Diets were manufactured at a commercial feed mill in southwestern Minnesota and offered in meal form.

Growth Performance and Carcass Characteristics

Pens of pigs were weighed and feed disappearance measured approximately every 2 wk to determine ADG, ADFI, and G:F. Besides determining overall performance, intermediate performance of the feeding strategies was compared with the performance of the 4-phase-feeding strategy within experiments, thus considering the 4-phase-feeding strategy with Lys specifications at 100% (experiments 1 and 2) or 98% (experiments 3 and 4) of estimated requirements as standard. The relative difference between feeding strategies was calculated as follows:

$$\text{Relative difference } (\%) = \left[\left(\frac{\text{ADG of feeding strategies}}{\text{ADG of four-phase feeding strategy}}\right) \times 100\right] - 100$$

At the end of the experimental period, pen weights were recorded and pigs were tattooed with a pen identification number and transported to a packing plant (JBS Swift and Co., Worthington, MN) for carcass data collection. Carcass measurements included HCW, back fat thickness, loin depth, and percentage lean. Carcass percentage lean was calculated from the packing plant

Table 1. Overview of experiments evaluating feeding strategies based on number of dietary phases (one, two, three, and four dietary phases) and lysine specifications (96%, 98%, and 100% of estimated requirements for growth rate) in the grow-finish period[1,2]

Approximate weight range, kg		27 to 50	50 to 72	72 to 100	100 to 127
Approximate duration, d		30	30	30	30
Dietary phases	Lysine specification	Lysine:calorie ratio[3]			
Experiment 1					
Two phase	100%	3.84	3.84	3.84	3.00
Four phase	100%	4.61	3.84	3.24	3.00
Four phase	96%	4.12	3.46	2.98	2.59
Four phase	96%/100%[4]	4.12	3.46	3.24	3.00
Experiment 2					
One phase	100%	3.23	3.23	3.23	3.23
Two phase	100%	3.83	3.83	3.83	3.01
Three phase	100%	4.57	3.51	3.51	3.01
Four phase	100%	4.57	3.81	3.21	3.01
Experiment 3					
One phase	98%	3.10	3.10	3.10	3.10
Two phase	98%	3.61	3.61	3.61	2.81
Three phase	98%	4.31	3.34	3.34	2.81
Four phase	98%	4.31	3.60	3.08	2.81
Experiment 4					
Two phase	98%	3.61	3.61	3.61	2.81
Two phase	98%/100%[5]	3.61	3.61	3.61	3.02
Three phase	98%	3.96	3.96	3.08	2.81
Four phase	98%	4.31	3.60	3.08	2.81

[1]A total of four experiments were conducted at a commercial research facility with 1,100 to 1,188 pigs (PIC 359 × 1050) per experiment in pens of 25 to 27 mixed-gender pigs per pen and 11 replicates per treatment. Experiments were conducted from ~27 to 127 kg BW for ~120 d. experiment 1 from 27.9 to 129.1 kg BW for 117 d, experiment 2 from 27.4 to 125.6 kg BW for 121 d, experiment 3 from 25.9 to 131.5 kg BW for 119 d, and experiment 4 from 28.8 to 129.9 kg BW for 114 d.
[2]Lysine specifications at 96%, 98%, and 100% of estimated requirements for growth rate were derived from the genetic supplier's lysine requirement prediction equation based on commercial experiments: standardized ileal digestible Lys, g/Mcal NE = $0.000056 \times (\text{BW, kg} \times 2.2046)^2 - 0.02844 \times (\text{BW, kg} \times 2.2046) + 6.6391$ (Genus PICGonçalves et al., 2017).
[3]Lysine:calorie ratio expressed as g of standardized ileal digestible lysine per Mcal of net energy.
[4]Lysine specifications at 96% of estimated requirements were applied in growing (27 to 72 kg BW) and lysine specifications at 100% of estimated requirements were applied in finishing (72 to 127 kg BW).
[5]Lysine specifications at 98% of estimated requirements were applied in growing-finishing (27 to 100 kg BW) and lysine specifications at 100% of estimated requirements were applied in late finishing (100 to 127 kg BW).

proprietary equation. Carcass yield was calculated by dividing the pen average HCW by the pen average live BW.

Chemical Analysis

Representative samples of complete feed were collected from multiple feeders per treatment during each dietary phase. Samples were stored at −20 °C until analysis. Composite samples were ground, subsampled, and analyzed (Ward Laboratories, Inc., Kearney, NE) for DM (method 935.29 AOAC, 1990), CP (method 990.03 AOAC, 1990), ether extract (**EE**; Ankom, 2004), NDF (Ankom, 1998), Ca (method 985.01 AOAC, 1990), and P (method 985.01 AOAC, 1990). In addition, composite samples were analyzed (Ajinomoto Heartland, Inc., Chicago, IL) for total AAs (method 994.12 for all except Trp and 994.13 for Trp, AOAC, 1990).

Statistical Analysis

Data were analyzed using a linear mixed model with treatment as fixed effect, block as random effect, and pen as the experimental unit. Data were modeled as normally distributed response variables as the residual analysis assumptions were met by evaluating studentized residuals. HCW was used as a covariate for analyses of back fat thickness, loin depth, and percentage lean. Statistical models were fit using the GLIMMIX procedure of SAS version 9.4 (SAS Institute, Inc., Cary, NC). Results were considered significant at $P \leq 0.05$ and a tendency at $0.05 < P \leq 0.10$.

Results And Discussion

Chemical Analysis

The analyzed DM, CP, EE, NDF, Ca, and P content of experimental diets were consistent with formulated estimates (Tables 2–5). The analyzed total AAs (not shown) and Lys (Tables 2–5) in experimental diets were within expectations considering expected analytical variation for complete feed analysis (AAFCO, 2018).

Growth Performance and Carcass Characteristics

Phase feeding is the strategy of feeding multiple diets during the grow-finish period to meet the continuously changing Lys requirements of pigs. Phase-feeding strategies with multiple dietary phases and frequent phase changes are more likely to closely meet the Lys requirements of grow-finish pigs and minimize the supply of Lys in deficiency or excess (Andretta et al., 2014). However, the manufacture, delivery, and storage logistics for multiple dietary phases are often not feasible in commercial swine production. Thus, simplification of phase-feeding strategies to fewer dietary phases in the grow-finish

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

Dietary phases	Two-phase		Four-phase				Four-phase				Four-phase			
Lysine specification	100%		100%				96%				96%/100%			
Initial weight, kg	27	100	27	50	72	100	27	50	72	100	27	50	72	100
Final weight, kg	100	127	50	72	100	127	50	72	100	127	50	72	100	127
Ingredient, %														
Corn	54.73	81.14	47.54	54.74	60.50	81.14	51.98	58.34	62.93	85.18	51.98	58.34	60.50	81.14
DDGS[3]	30.00	—	30.00	30.00	30.00	—	30.00	30.00	30.00	—	30.00	30.00	30.00	—
Soybean meal, 47% CP	12.13	16.05	19.09	12.13	6.41	16.05	14.60	8.46	3.96	11.97	14.60	8.46	6.41	16.05
Tallow	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Monocalcium phosphate, 21% P	0.05	0.25	0.20	0.05	—	0.25	0.25	0.10	—	0.30	0.25	0.10	—	0.25
Calcium carbonate	1.20	0.95	1.28	1.20	1.20	0.95	1.30	1.23	1.23	0.95	1.30	1.23	1.20	0.95
Sodium chloride	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
L-Lysine HCl	0.50	0.25	0.50	0.50	0.50	0.25	0.50	0.50	0.50	0.25	0.50	0.50	0.50	0.25
DL-Methionine	—	0.02	0.02	—	—	0.02	—	—	—	0.01	—	—	—	0.02
L-Threonine	0.09	0.07	0.09	0.08	0.08	0.07	0.08	0.08	0.07	0.06	0.08	0.08	0.08	0.07
L-Tryptophan	0.05	0.02	0.03	0.04	0.05	0.02	0.03	0.04	0.05	0.02	0.03	0.04	0.05	0.02
Vitamin–trace mineral premix[4]	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Calculated analysis														
SID[5] AAs, %														
Lysine	0.96	0.77	1.13	0.96	0.82	0.77	1.02	0.87	0.76	0.67	1.02	0.87	0.82	0.77
Isoleucine:lysine	62	64	63	62	61	64	62	61	60	63	62	61	61	64
Leucine:lysine	173	154	161	173	186	154	168	180	193	163	168	180	186	154
Methionine:lysine	31	30	30	31	33	30	30	32	34	30	30	32	33	30
Methionine and cysteine:lysine	59	58	57	59	63	58	57	61	65	60	57	61	63	58
Threonine:lysine	64	65	62	63	64	65	62	63	64	65	62	63	64	65
Tryptophan:lysine	19.8	19.5	18.9	18.7	19.9	19.5	18.5	18.9	19.7	19.8	18.5	18.9	19.9	19.5
Valine:lysine	75	73	74	75	76	73	74	76	77	74	74	76	76	73
Total lysine, %	1.13	0.88	1.32	1.13	0.97	0.88	1.19	1.03	0.91	0.76	1.19	1.03	0.97	0.88
NE, kcal/kg	2,498	2,566	2,452	2,498	2,533	2,566	2,476	2,518	2,546	2,588	2,476	2,518	2,533	2,566
SID Lys:NE, g/Mcal	3.84	3.00	4.61	3.84	3.24	3.00	4.12	3.46	2.98	2.59	4.12	3.46	3.24	3.00
CP, %	18.6	13.6	21.4	18.6	16.3	13.6	19.6	17.1	15.3	12.0	19.6	17.1	16.3	13.6
Calcium, %	0.53	0.45	0.60	0.53	0.50	0.45	0.60	0.53	0.50	0.45	0.60	0.53	0.50	0.45
STTD[6] phosphorus, %	0.33	0.26	0.38	0.33	0.30	0.26	0.38	0.33	0.30	0.26	0.38	0.33	0.30	0.26
Chemical analysis[7]														
DM, %	88.1	87.2	87.7	87.5	88.1	87.1	87.1	88.1	88.2	87.4	87.4	87.5	88.4	87.0
CP, %	18.0	13.3	19.7	20.2	16.4	13.1	18.9	18.8	15.0	12.1	18.5	17.0	16.0	13.8
EE, %	4.9	3.4	5.4	4.8	5.1	3.5	5.0	4.9	5.0	3.5	4.7	5.0	5.3	3.1
NDF, %	11.5	5.7	13.7	12.9	12.6	5.6	11.8	12.5	11.3	5.4	11.4	11.2	13.0	5.3
Calcium, %	0.66	0.53	0.67	0.83	0.58	0.52	0.69	0.73	0.77	0.53	0.72	0.70	0.52	0.57
Phosphorus, %	0.46	0.34	0.50	0.47	0.44	0.34	0.49	0.51	0.40	0.33	0.47	0.45	0.43	0.34

Table 2. Continued

Dietary phases	Two-phase		Four-phase				Four-phase				Four-phase			
Lysine specification	100%		100%				96%				96%/100%			
Initial weight, kg	27	100	27	50	72	100	27	50	72	100	27	50	72	100
Final weight, kg	100	127	50	72	100	127	50	72	100	127	50	72	100	127
Lysine, %	1.05	0.84	1.19	1.15	0.92	0.78	1.12	1.10	0.83	0.71	1.11	0.97	0.93	0.79

[1]Experiment evaluated feeding strategies based on number of dietary phases (two and four dietary phases) and lysine specifications (96% and 100% of estimated requirements for growth rate) for grow-finish pigs. Lysine specifications were derived from the genetic supplier's lysine requirement prediction equation based on commercial experiments (Genus PIC; Gonçalves et al., 2017). For 96%/100%, lysine specifications for 96% of estimated requirements were applied in growing (27 to 72 kg BW) and lysine specifications for 100% of estimated requirements were applied in finishing (72 to 127 kg BW).
[2]Diets were fed ad libitum in meal form from 27.9 to 129.1 kg BW for 117 d. Lysine levels in experimental diets were achieved by changing the inclusion of soybean meal.
[3]DDGS = corn distillers dried grains with solubles.
[4]Provided per kilogram of premix: 3,527,360 IU vitamin A; 881,840 IU vitamin D; 17,637 IU vitamin E; 1,764 mg vitamin K; 15.4 mg vitamin B_{12}; 33,069 mg niacin; 11,023 mg pantothenic acid; 3,307 mg riboflavin; 74 g Zn from zinc sulfate; 74 g Fe from iron sulfate; 22 g Mn from manganese oxide; 11 g Cu from copper sulfate; 0.22 g I from calcium iodate; 0.20 g Se from sodium selenite; 500,000 FTU phytase from OptiPhos 2000 (Huvepharma Inc., Peachtree City, GA).
[5]SID = standardized ileal digestible.
[6]STTD = standardized total tract digestible.
[7]Representative samples of complete feed were collected from multiple feeders and composite samples were ground, subsampled, and analyzed (Ward Laboratories, Inc., Kearney, NE for proximate analysis and Ajinomoto Heartland, Inc., Chicago, IL for lysine analysis).

period is a topic of growing interest (Moore et al., 2012; Hong et al., 2016; Presto Åkerfeldt et al., 2019). Phase-feeding strategies with fewer dietary phases typically provide at or below Lys requirements initially and provide adequate or excess Lys levels later in the phase, and generally rely on compensatory growth to ensure optimal growth performance and carcass characteristics (O'Connell et al., 2005; Garry et al., 2007). The number of dietary phases and Lys specifications comprising phase-feeding strategies requires careful consideration to ensure optimal growth performance and carcass characteristics of grow-finish pigs. Thus, the present study aimed to evaluate and provide scientific support to the widespread practice of phase feeding in swine production, as current peer-reviewed publications with grow-finish pigs reared in commercial conditions are needed.

Growth performance in the overall grow-finish period is presented in Table 6 for all experiments. The first experiment was conducted to evaluate feeding strategies with distinct Lys specifications (96% vs. 100% of estimated requirements). The use of Lys specifications at 96% of estimated requirements in a 4-phase-feeding strategy reduced ($P < 0.05$) overall ADG and led to numerically ($P > 0.10$) lower final live BW by 2.5 kg and HCW by 1.5 kg, approximately, compared with feeding strategies with Lys at 100% of estimated requirements. However, there was no evidence ($P > 0.05$) that Lys specifications at 96% of estimated requirements in the growing phase compromised overall growth performance and final BW provided that Lys specifications were increased to 100% of estimated requirements in the late finishing phase. In agreement with Main et al. (2008), as long as Lys requirements are met in late finishing, using Lys below the requirements in early growing does not impact overall growth performance. Interestingly, Lys specifications at 100% of estimated requirements in either a 2- or 4-phase feeding strategy led to similar overall growth performance of grow-finish pigs. The benefits of multiple dietary phases in phase-feeding strategies seems to be less evident when using Lys at the requirements, as previously proposed by Garry et al. (2007).

The second experiment was conducted to evaluate the effects of 1, 2, 3, or 4 dietary phases with Lys specifications at 100% of estimated requirements. A single-phase-feeding strategy reduced ($P < 0.05$) overall ADG, live BW, and HCW compared with multi-phase-feeding strategies. In contrast, previous studies have found no evidence for impact on growth performance by having a single dietary phase during the grow-finish period (Bradford and Gous, 1991; Lee et al., 2000; O'Connell et al., 2005; Garry et al., 2007; Moore et al., 2012). The divergence from the present study could be due to differences in Lys levels and weight range of the phase-feeding strategies used in the studies, as well as experimental conditions. Among the phase-feeding strategies, either a 2-, 3- or 4-phase-feeding strategy resulted in no evidence for difference ($P > 0.10$) in overall ADG and final BW of grow-finish pigs, which is in agreement with previous studies (Bradford and Gous, 1991; Lee et al., 2000; Hong et al., 2016). Validating the findings in experiment 1, simplification of phase-feeding strategies to fewer dietary phases in the grow-finish period with Lys set at the estimated requirements seems feasible.

The third experiment was conducted to evaluate whether simplification of phase-feeding strategies could be implemented with Lys below the requirements. Because Lys specifications at 96% of estimated requirements negatively affected growth performance in experiment 1, Lys specifications at 98% of estimated requirements were used. Validating the findings in experiment 2, a single-phase-feeding strategy reduced ($P < 0.05$) overall ADG, G:F, live BW, and HCW

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

Dietary phases	One-phase	Two-phase		Three-phase			Four-phase			
Lysine specification	100%	100%		100%			100%			
Initial weight, kg	27	27	100	27	50	100	27	50	72	100
Final weight, kg	127	100	127	50	100	127	50	72	100	127
Ingredient, %										
Corn	68.64	62.98	69.87	56.09	66.17	69.87	56.09	63.32	69.16	69.87
DDGS[3]	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
Soybean meal, 47% CP	7.68	13.39	7.19	20.33	10.51	7.19	20.33	13.37	7.64	7.19
Tallow	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Monocalcium phosphate, 21% P	0.55	0.50	---	0.40	0.25	---	0.40	0.25	0.10	---
Calcium carbonate	1.23	1.20	1.10	1.20	1.15	1.10	1.20	1.13	1.18	1.10
Sodium chloride	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
L-Lysine HCl	0.50	0.50	0.45	0.50	0.50	0.45	0.50	0.50	0.50	0.45
DL-Methionine	—	0.03	—	0.07	0.01	—	0.07	0.03	—	—
L-Threonine	0.10	0.11	0.09	0.13	0.11	0.09	0.13	0.11	0.11	0.09
L-Tryptophan	0.05	0.04	0.05	0.04	0.04	0.05	0.04	0.04	0.05	0.05
Vitamin–trace mineral premix[4]	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Calculated analysis										
SID[5] AAs, %										
Lysine	0.82	0.96	0.77	1.13	0.89	0.77	1.13	0.96	0.82	0.77
Isoleucine:lysine	57	58	59	60	58	59	60	58	57	59
Leucine:lysine	166	156	176	147	161	176	147	156	166	176
Methionine:lysine	29	30	31	32	30	31	32	30	29	31
Methionine and cysteine:lysine	57	57	60	57	57	60	57	57	57	60
Threonine:lysine	63	63	64	63	63	64	63	63	64	64
Tryptophan:lysine	18.8	18.9	19.7	19.0	18.6	19.7	19.0	18.9	19.4	19.7
Valine:lysine	70	69	73	69	70	73	69	69	70	73
Total lysine, %	0.95	1.11	0.90	1.29	1.03	0.90	1.29	1.11	0.95	0.90
NE, kcal/kg	2,540	2,509	2,562	2,471	2,535	2,562	2,471	2,518	2,555	2,562
SID Lys:NE, g/Mcal	3.23	3.83	3.01	4.57	3.51	3.01	4.57	3.81	3.21	3.01
CP, %	14.7	17.0	14.5	19.9	15.8	14.5	19.9	17.0	14.7	14.5
Calcium, %	0.60	0.60	0.46	0.60	0.53	0.46	0.60	0.53	0.50	0.46
STTD[6] phosphorus, %	0.38	0.38	0.27	0.38	0.33	0.27	0.38	0.33	0.29	0.27
Chemical analysis[7]										
DM, %	88.2	88.1	87.9	89.0	88.2	87.5	88.9	88.0	88.6	87.1
CP, %	14.3	16.7	15.1	20.3	16.4	15.0	17.9	16.3	15.0	15.2
EE, %	4.2	4.2	4.6	4.1	4.5	4.5	4.3	4.3	4.5	4.1
NDF, %	10.0	10.4	10.2	10.4	9.9	10.3	10.8	9.8	10.0	9.6
Calcium, %	0.80	0.75	0.63	0.81	0.68	0.47	0.68	0.71	0.57	0.74
Phosphorus, %	0.49	0.51	0.38	0.51	0.44	0.37	0.46	0.44	0.40	0.36
Lysine, %	0.90	1.03	0.90	1.25	0.99	0.92	1.08	1.04	0.88	0.99

[1]Experiment evaluated feeding strategies based on number of dietary phases (one, two, three, and four dietary phases) with lysine specifications at 100% of estimated requirement for growth rate for grow-finish pigs. Lysine specifications were derived from the genetic supplier's lysine requirement prediction equation based on commercial experiments (Genus PIC; Gonçalves et al., 2017).

[2]Diets were fed ad libitum in meal form from 27.4 to 125.6 kg BW for 121 d. Lysine levels in experimental diets were achieved by changing the inclusion of soybean meal.

[3]DDGS = corn distillers dried grains with solubles.

[4]Provided per kilogram of premix: 3,527,360 IU vitamin A; 881,840 IU vitamin D; 17,637 IU vitamin E; 1,764 mg vitamin K; 15.4 mg vitamin B_{12}; 33,069 mg niacin; 11,023 mg pantothenic acid; 3,307 mg riboflavin; 74 g Zn from zinc sulfate; 74 g Fe from iron sulfate; 22 g Mn from manganese oxide; 11 g Cu from copper sulfate; 0.22 g I from calcium iodate; 0.20 g Se from sodium selenite; 500,000 FTU phytase from OptiPhos 2000 (Huvepharma Inc., Peachtree City, GA).

[5]SID = standardized ileal digestible.

[6]STTD = standardized total tract digestible.

[7]Representative samples of complete feed were collected from multiple feeders and composite samples were ground, subsampled, and analyzed (Ward Laboratories, Inc., Kearney, NE for proximate analysis and Ajinomoto Heartland, Inc., Chicago, IL for lysine analysis).

compared with multi-phase-feeding strategies. Among the phase-feeding strategies, either a 2-, 3- or 4-phase-feeding strategy led to similar ($P > 0.05$) overall ADG and final BW of grow-finish pigs. However, a 2- or 3-phase-feeding strategy reduced ($P < 0.05$) overall G:F compared with a 4-phase feeding strategy. A previous study by Lee et al. (2000) corroborates the improvement in feed efficiency in 4-phase compared to 2- or 3-phase feeding strategy. Because Lys is an important component to efficient lean growth (van Milgen and Dourmad, 2015), it seems more critical to set Lys closely to the estimated

Table 4. Composition of experimental diets (as-fed basis), experiment 3[1,2]

Dietary phases	One-phase	Two-phase		Three-phase			Four-phase			
Lysine specification	98%	98%		98%			98%			
Initial weight, kg	27	27	100	27	50	100	27	50	72	100
Final weight, kg	127	100	127	50	100	127	50	72	100	127
Ingredient, %										
Corn	69.81	64.99	80.21	58.50	67.75	80.21	58.50	65.34	70.38	80.21
DDGS[3]	20.00	20.00	—	20.00	20.00	—	20.00	20.00	20.00	—
Soybean meal, 47% CP	6.46	11.35	17.21	17.88	8.88	17.21	17.88	11.33	6.42	17.21
Tallow	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Monocalcium phosphate, 21% P	0.60	0.50	0.20	0.45	0.30	0.20	0.45	0.25	0.10	0.20
Calcium carbonate	1.23	1.23	0.95	1.20	1.15	0.95	1.20	1.15	1.18	0.95
Sodium chloride	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
L-Lysine HCl	0.50	0.50	0.15	0.50	0.50	0.15	0.50	0.50	0.50	0.15
DL-Methionine	—	0.03	—	0.06	0.02	—	0.06	0.03	—	—
L-Threonine	0.10	0.11	0.02	0.12	0.11	0.02	0.12	0.11	0.11	0.02
L-Tryptophan	0.05	0.04	—	0.04	0.05	—	0.04	0.04	0.06	—
Vitamin–trace mineral premix[4]	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Calculated analysis										
SID[5] AAs, %										
Lysine	0.79	0.91	0.72	1.07	0.85	0.72	1.07	0.91	0.79	0.72
Isoleucine:lysine	56	58	71	59	57	71	59	58	56	71
Leucine:lysine	168	159	169	150	164	169	150	159	169	169
Methionine:lysine	30	31	31	32	31	31	32	31	30	31
Methionine and cysteine:lysine	58	58	62	58	58	62	58	58	58	62
Threonine:lysine	63	63	64	63	63	64	63	63	64	64
Tryptophan:lysine	18.7	18.6	19.7	18.8	19.0	19.7	18.8	18.6	19.9	19.7
Valine:lysine	70	69	81	69	70	81	69	69	70	81
Total lysine, %	0.92	1.05	0.83	1.23	0.98	0.83	1.23	1.05	0.92	0.83
NE, kcal/kg	2,546	2,520	2,560	2,485	2,542	2,560	2,485	2,529	2,562	2,560
SID Lys:NE, g/Mcal	3.10	3.61	2.81	4.31	3.34	2.81	4.31	3.60	3.08	2.81
CP, %	14.2	16.2	14.0	18.9	15.2	14.0	18.9	16.2	14.2	14.0
Calcium, %	0.60	0.60	0.45	0.60	0.53	0.45	0.60	0.53	0.50	0.45
STTD[6] phosphorus, %	0.38	0.38	0.26	0.38	0.33	0.26	0.38	0.33	0.29	0.26
Chemical analysis[7]										
DM, %	87.8	87.7	87.0	88.6	87.3	87.7	88.2	88.8	87.0	87.3
CP, %	14.4	16.4	13.6	19.2	15.6	14.5	19.0	17.5	13.6	13.6
EE, %	4.1	3.7	3.3	3.6	3.4	3.3	3.7	3.9	3.3	3.4
NDF, %	9.5	9.1	6.6	10.6	7.8	6.4	10.0	9.9	6.9	6.7
Calcium, %	0.74	0.64	0.56	0.77	0.55	0.42	0.77	0.73	0.59	0.56
Phosphorus, %	0.51	0.45	0.33	0.52	0.40	0.35	0.50	0.46	0.34	0.34
Lysine, %	0.94	0.98	0.88	1.21	0.88	0.80	1.19	1.02	0.79	0.88

[1]Experiment evaluated feeding strategies based on number of dietary phases (one, two, three, and four dietary phases) with lysine specifications at 98% of estimated requirements for growth rate for grow-finish pigs. Lysine specifications were derived from the genetic supplier's lysine requirement prediction equation based on commercial experiments (Genus PIC; Gonçalves et al., 2017).
[2]Diets were fed ad libitum in meal form from 25.9 to 131.5 kg BW for 119 d. Lysine levels in experimental diets were achieved by changing the inclusion of soybean meal.
[3]DDGS = corn distillers dried grains with solubles.
[4]Provided per kilogram of premix: 3,527,360 IU vitamin A; 881,840 IU vitamin D; 17,637 IU vitamin E; 1,764 mg vitamin K; 15.4 mg vitamin B_{12}; 33,069 mg niacin; 11,023 mg pantothenic acid; 3,307 mg riboflavin; 74 g Zn from zinc sulfate; 74 g Fe from iron sulfate; 22 g Mn from manganese oxide; 11 g Cu from copper sulfate; 0.22 g I from calcium iodate; 0.20 g Se from sodium selenite; 500,000 FTU phytase from OptiPhos 2000 (Huvepharma Inc., Peachtree City, GA).
[5]SID = standardized ileal digestible.
[6]STTD = standardized total tract digestible.
[7]Representative samples of complete feed were collected from multiple feeders and composite samples were ground, subsampled, and analyzed (Ward Laboratories, Inc., Kearney, NE for proximate analysis and Ajinomoto Heartland, Inc., Chicago, IL for lysine analysis).

requirements in phase-feeding strategies with fewer dietary phases.

The last experiment was conducted to evaluate whether increasing Lys levels from 98% to 100% of estimated requirements in late finishing in a 2-phase feeding strategy or decreasing Lys levels earlier instead of later in a 3-phase-feeding strategy with Lys at 98% of estimated requirements could lead to similar overall growth performance to a 4-phase feeding strategy with

Table 5. Composition of experimental diets (as-fed basis), experiment 4[1,2]

Dietary phases	Two-phase		Two-phase		Three-phase			Four-phase			
Lysine specification	98%		98%/100%		98%			98%			
Initial weight, kg	27	100	27	100	27	72	100	27	50	72	100
Final weight, kg	100	127	100	127	72	100	127	50	72	100	127
Ingredient, %											
Corn	64.98	80.21	64.98	78.17	61.76	70.39	80.21	58.48	65.33	70.39	80.21
DDGS[3]	20.00	—	20.00	—	20.00	20.00	—	20.00	20.00	20.00	—
Soybean meal, 47% CP	11.35	17.21	11.35	19.25	14.61	6.42	17.21	17.88	11.33	6.42	17.21
Tallow	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Monocalcium phosphate, 21% P	0.50	0.20	0.50	0.20	0.45	0.10	0.20	0.45	0.25	0.10	0.20
Calcium carbonate	1.23	0.95	1.23	0.95	1.23	1.18	0.95	1.20	1.15	1.18	0.95
Sodium chloride	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
L-Lysine HCl	0.50	0.15	0.50	0.15	0.50	0.50	0.15	0.50	0.50	0.50	0.15
DL-Methionine	0.03	—	0.03	—	0.03	—	—	0.06	0.03	—	—
L-Threonine	0.12	0.02	0.12	0.02	0.13	0.11	0.02	0.13	0.12	0.11	0.02
L-Tryptophan	0.05	—	0.05	—	0.04	0.05	—	0.04	0.05	0.05	—
Vitamin–trace mineral premix[4]	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Calculated analysis											
SID[5] AAs, %											
Lysine	0.91	0.72	0.91	0.77	0.99	0.79	0.72	1.07	0.91	0.79	0.72
Isoleucine:lysine	58	71	58	71	59	56	71	59	58	56	71
Leucine:lysine	159	169	159	164	154	169	169	149	159	169	169
Methionine:lysine	31	31	31	30	30	30	31	32	31	30	31
Methionine and cysteine:lysine	58	62	58	60	56	58	62	58	58	58	62
Threonine:lysine	64	64	64	64	64	64	64	64	64	64	64
Tryptophan:lysine	19.2	19.7	19.2	19.9	19.0	19.3	19.7	19.2	19.2	19.3	19.7
Valine:lysine	69	81	69	80	69	70	81	69	69	70	81
Total lysine, %	1.05	0.83	1.05	0.88	1.14	0.92	0.83	1.23	1.05	0.92	0.83
NE, kcal/kg	2,522	2,560	2,522	2,549	2,502	2,562	2,560	2,485	2,531	2,562	2,560
SID Lys:NE, g/Mcal	3.61	2.81	3.61	3.02	3.96	3.08	2.81	4.31	3.60	3.08	2.81
CP, %	16.2	14.0	16.2	14.8	17.5	14.2	14.0	18.9	16.2	14.2	14.0
Calcium, %	0.60	0.45	0.60	0.45	0.60	0.50	0.45	0.60	0.53	0.50	0.45
STTD[6] phosphorus, %	0.38	0.26	0.38	0.26	0.38	0.29	0.26	0.38	0.33	0.29	0.26
Chemical analysis[7]											
DM, %	87.8	87.9	87.3	87.9	87.7	86.6	87.0	88.6	87.4	87.7	87.9
CP, %	15.8	14.2	14.8	14.1	18.7	13.7	13.1	16.8	14.7	13.7	13.1
EE, %	3.8	3.3	3.4	3.3	3.8	3.4	3.8	4.2	4.0	3.6	4.1
NDF, %	8.9	7.2	7.4	6.5	8.7	6.2	7.5	10.2	10.2	7.5	7.7
Calcium, %	0.70	0.55	0.62	0.67	0.67	0.62	0.64	0.65	0.67	0.57	0.72
Phosphorus, %	0.45	0.37	0.39	0.36	0.46	0.33	0.38	0.44	0.37	0.34	0.41
Lysine, %	0.93	0.81	0.89	0.80	1.20	0.82	0.71	1.02	0.90	0.82	0.73

[1]Experiment evaluated feeding strategies based on number of dietary phases (two, three, and four dietary phases) and lysine specifications (98% and 100% of estimated requirements for growth rate) for grow-finish pigs. Lysine specifications were derived from the genetic supplier's lysine requirement prediction equation based on commercial experiments (Genus PIC; Gonçalves et al., 2017). For 98%/100%, lysine specifications at 98% of estimated requirements were applied in growing-finishing (27 to 100 kg BW) and lysine specifications at 100% of estimated requirements were applied in late finishing (100 to 127 kg BW).
[2]Diets were fed ad libitum in meal form from 28.8 to 129.9 kg BW for 114 d. Lysine levels in experimental diets were achieved by changing the inclusion of soybean meal.
[3]DDGS = corn distillers dried grains with solubles.
[4]Provided per kilogram of premix: 3,527,360 IU vitamin A; 881,840 IU vitamin D; 17,637 IU vitamin E; 1,764 mg vitamin K; 15.4 mg vitamin B_{12}; 33,069 mg niacin; 11,023 mg pantothenic acid; 3,307 mg riboflavin; 74 g Zn from zinc sulfate; 74 g Fe from iron sulfate; 22 g Mn from manganese oxide; 11 g Cu from copper sulfate; 0.22 g I from calcium iodate; 0.20 g Se from sodium selenite; 500,000 FTU phytase from OptiPhos 2000 (Huvepharma Inc., Peachtree City, GA).
[5]SID = standardized ileal digestible.
[6]STTD = standardized total tract digestible.
[7]Representative samples of complete feed were collected from multiple feeders and composite samples were ground, subsampled, and analyzed (Ward Laboratories, Inc., Kearney, NE for proximate analysis and Ajinomoto Heartland, Inc., Chicago, IL for lysine analysis).

Lys at 98% of estimated requirements. Indeed, both approaches resulted in no evidence for difference ($P > 0.05$) in overall growth performance compared to a 4-phase feeding strategy even with Lys levels below the requirements. However, in contrast to experiment 3, the 2-phase-feeding strategy with Lys at 98% of estimated requirements led to similar ($P > 0.05$) overall growth performance and final BW to a 4-phase-feeding strategy with Lys at 98% of estimated requirements. Although unexpected, the discrepancy between experiments could be attributed to a difference in initial BW and overall feed intake. In experiment 3,

Table 6. Effects of feeding strategies based on number of dietary phases (one, two, three, and four dietary phases) and lysine specifications (96%, 98%, and 100% of estimated requirements for growth rate) on growth performance of grow-finish pigs[1,2]

Item	Experiment 1					
Overall, days 0 to 117	Two-phase 100%	Four-phase 100%	Four-phase 96%	Four-phase 96%/100%	SEM	P
Initial BW, kg	27.9	27.9	27.9	27.9	0.79	<0.998
Final BW, kg	129.9	129.8	127.2	129.4	1.09	<0.110
ADG, kg	0.880[a]	0.876[ab]	0.855[b]	0.870[ab]	0.006	<0.044
ADFI, kg	2.29	2.29	2.26	2.28	0.022	0.514
G:F	0.385	0.382	0.379	0.381	0.003	0.202
	Experiment 2					
Overall, days 0 to 121	One-phase 100%	Two-phase 100%	Three-phase 100%	Four-phase 100%	SEM	P
Initial BW, kg	27.4	27.4	27.4	27.4	0.66	<0.951
Final BW, kg	123.9[y]	126.2[xy]	125.5[xy]	126.7[x]	1.16	<0.051
ADG, kg	0.797[b]	0.816[a]	0.814[ab]	0.822[a]	0.006	<0.007
ADFI, kg	2.24	2.29	2.26	2.30	0.031	<0.126
G:F	0.356	0.357	0.361	0.357	0.004	<0.398
	Experiment 3					
Overall, days 0 to 119	One-phase 98%	Two-phase 98%	Three-phase 98%	Four-phase 98%	SEM	P
Initial BW, kg	25.9	25.9	25.8	25.9	0.31	<0.997
Final BW, kg	129.1[b]	131.6[ab]	131.8[ab]	133.4[a]	1.10	<0.022
ADG, kg	0.862[b]	0.881[ab]	0.887[ab]	0.899[a]	0.008	<0.009
ADFI, kg	2.29	2.29	2.31	2.29	0.024	<0.953
G:F	0.376[c]	0.385[b]	0.385[b]	0.392[a]	0.002	<0.001
	Experiment 4					
Overall, days 0 to 114	Two-phase 98%	Two-phase 98%/100%	Three-phase 98%	Four-phase 98%	SEM	P
Initial BW, kg	28.7	28.9	28.9	28.9	0.47	<0.593
Final BW, kg	128.8	130.3	130.9	129.6	1.05	<0.317
ADG, kg	0.895	0.907	0.911	0.899	0.006	<0.215
ADFI, kg	2.36	2.40	2.42	2.39	0.025	<0.305
G:F	0.379	0.378	0.376	0.376	0.003	<0.765

[1]A total of four experiments were conducted at a commercial research facility with 1,100 to 1,188 pigs (PIC 359 × 1,050) per experiment in pens of 25 to 27 mixed-gender pigs per pen and 11 replicates per treatment. Experiments were conducted from ~27 to 127 kg BW for 120 d.
[2]Lysine specifications at 96%, 98%, and 100% of estimated requirements for growth rate were derived from the genetic supplier's lysine requirement prediction equation based on commercial experiments (Genus PIC; Gonçalves et al., 2017). For 96%/100%, lysine specifications at 96% of estimated requirements were applied in growing (27 to 72 kg BW) and lysine specifications at 100% of estimated requirements were applied in finishing (72 to 127 kg BW). For 98%/100%, lysine specifications at 98% of estimated requirements were applied in growing-finishing (27 to 100 kg BW) and lysine specifications at 100% of estimated requirements were applied in late finishing (100 to 127 kg BW).
[abc]Means with different superscripts are significantly different ($P \leq 0.05$) in the row.
[xy]Means with different superscripts have a tendency to be different ($0.05 < P \leq 0.10$) in the row.

initial BW and overall feed intake were approximately 10% and 4% lower, respectively, compared with experiment 4. Thus, in experiment 3 initial Lys levels were further below the estimated requirements in the early grow-finish period and Lys intake in the entire grow-finish period was lower. In agreement with previous studies (O'Connell et al., 2005; Garry et al., 2007; Presto Åkerfeldt et al., 2019), simplification of phase-feeding strategies to fewer dietary phases in the grow-finish period with Lys set slightly below the estimated requirements seems feasible. However, in feeding programs with fewer dietary phases and Lys set slightly below the requirements, growth performance can be compromised if initial BW and feed intake in the grow-finish period are lower than expected.

For carcass characteristics, there was no evidence ($P > 0.10$) for differences in carcass yield, back fat, loin depth, or lean percentage across feeding strategies in any of the experiments (Table 7). Thus, the influence of phase-feeding strategies on carcass characteristics was not detected except for effects on HCW driven by differences in live BW. In agreement, previous phase-feeding studies have found no evidence for influence of number of dietary phases on carcass characteristics (O'Connell et al., 2005; Garry et al., 2007; Moore et al., 2012; Hong et al., 2016). Lee et al. (2000) observed a tendency for an increase in back fat thickness in pigs fed a single-phase compared with multi-phase-feeding strategies. Lipid deposition tends to increase in a single-phase strategy due to the typically low Lys levels in the early grow-finish period which coincides with the period of greater potential for lean deposition (Lee et al., 2000). In the present study, only a numeric increase in back fat thickness was observed in pigs under the single-phase-feeding strategies compared with multi-phase-feeding strategies. The variation in carcass yield across experiments is likely attributed to DDGS inclusion rate in the diets and its influence on NDF level and, consequently, carcass yield (Soto et al., 2019).

Compensatory growth is a physiological process whereby animals undergo a period of accelerated growth following a period of nutritional restriction (Hornick et al., 2000; O'Connell et al., 2006). Compensatory growth induced by Lys restriction

Table 7. Effects of feeding strategies based on number of dietary phases (one, two, three, and four dietary phases) and lysine specifications (96%, 98%, and 100% of estimated requirements for growth rate) on carcass characteristics of grow-finish pigs[1,2]

Item	Experiment 1					
	Two-phase 100%	Four-phase 100%	Four-phase 96%	Four-phase 96%/100%	SEM	P
HCW, kg	94.6	94.2	92.7	94.0	0.81	<0.219
Yield, %	72.8	72.6	72.9	72.6	0.15	<0.338
Back fat[3], mm	17.0	16.6	17.1	17.0	0.31	<0.450
Loin depth[3], mm	68.7	68.4	68.3	67.6	0.57	<0.459
Lean[3], %	56.7	57.0	56.6	56.6	0.22	<0.430
	Experiment 2					
	One-phase 100%	Two-phase 100%	Three-phase 100%	Four-phase 100%	SEM	P
HCW, kg	95.1[b]	97.6[a]	96.4[ab]	97.8[a]	1.05	<0.014
Yield, %	76.8	77.4	76.8	77.2	0.22	<0.120
Back fat[3], mm	16.8	16.3	16.5	16.3	0.24	<0.365
Loin depth[3], mm	68.1	68.3	66.8	67.1	0.59	<0.111
Lean[3], %	56.8	57.1	56.8	57.0	0.19	<0.519
	Experiment 3					
	One-phase 98%	Two-phase 98%	Three-phase 98%	Four-phase 98%	SEM	P
HCW, kg	95.4[b]	97.0[ab]	97.6[ab]	98.6[a]	0.73	<0.005
Yield, %	74.0	73.7	74.1	74.0	0.37	<0.932
Back fat[3], mm	17.0	16.7	16.8	16.4	0.27	<0.429
Loin depth[3], mm	67.5	68.8	67.6	68.0	0.61	<0.400
Lean[3], %	56.6	56.9	56.7	57.0	0.21	<0.411
	Experiment 4					
	Two-phase 98%	Two-phase 98%/100%	Three-phase 98%	Four-phase 98%	SEM	P
HCW, kg	95.3	96.0	96.9	96.2	0.66	<0.231
Yield, %	74.1	73.7	74.1	74.2	0.32	<0.652
Back fat[3], mm	16.5	17.1	16.8	16.6	0.28	<0.582
Loin depth[3], mm	68.9	68.6	68.8	69.9	0.52	<0.327
Lean[3], %	57.0	56.7	56.8	57.1	0.20	<0.487

[1]A total of four experiments were conducted at a commercial research facility with 1,100 to 1,188 pigs (PIC 359 × 1,050) per experiment in pens of 25 to 27 mixed-gender pigs per pen and 11 replicates per treatment. Experiments were conducted from ~27 to 127 kg BW for ~120 d.
[2]Lysine specifications at 96%, 98%, and 100% of estimated requirements for growth rate were derived from the genetic supplier's lysine requirement prediction equation based on commercial experiments (Genus PIC; Gonçalves et al., 2017). For 96%/100%, lysine specifications at 96% of estimated requirements were applied in growing (27 to 72 kg BW) and lysine specifications at 100% of estimated requirements were applied in finishing (72 to 127 kg BW). For 98%/100%, lysine specifications at 98% of estimated requirements were applied in growing-finishing (27 to 100 kg BW) and lysine specifications at 100% of estimated requirements were applied in late finishing (100 to 127 kg BW).
[3]Adjusted using HCW as covariate.
[abc]Means with different superscripts are significantly different ($P \le 0.05$) in the row.

in grow-finish pigs has been previously described (Chiba et al., 2002; Reynolds and O'Doherty, 2006; Suárez-Belloch et al., 2015). Although the present study was not purposefully designed to evaluate compensatory growth, there were indications of compensatory growth induced by previous Lys restriction. The influence of Lys levels in the grow-finish period on ADG is illustrated in Figure 1. The initial low Lys levels of 1- and 2-phase-feeding strategies or feeding strategies with Lys below the requirements in the early grow-finish (96%/100% and 98%/100%) led to considerable decrease in ADG during the period of 27 to 50 or 27 to 72 kg BW compared with 4-phase-feeding strategies. However, the following adequate Lys levels led to a substantial increase in ADG compared with 4-phase-feeding strategies, even though in some instances the dietary Lys levels were the same as those provided to pigs on 4-phase-feeding strategies. The improvement in growth rate in the period following Lys restriction was mainly driven by feed efficiency and indicates the occurrence of compensatory growth. Compensatory growth is a complex phenomenon affected by a number of factors and interactions. Particularly in the present study, severe Lys restriction, long restriction duration, and low Lys level following restriction seem to critically impair the ability of occurrence of complete or incomplete compensatory growth. This is evidenced by the inability of pigs fed 1-phase-feeding strategies to completely compensate to achieve similar performance as pigs fed 4-phase-feeding strategies, as well as by the distinct ability of pigs fed 2-phase-feeding strategies across experiments to completely compensate to achieve similar performance as pigs fed 4-phase-feeding strategies based on Lys specifications, initial Lys restriction, and Lys intake. Interestingly, pigs fed 3-phase-feeding strategies with low Lys levels earlier in the growing period (experiment 4) seem to have the ability to compensate, whereas pigs fed three-phase-feeding strategies with low Lys levels later in the finishing period (experiments 2 and 3) do not.

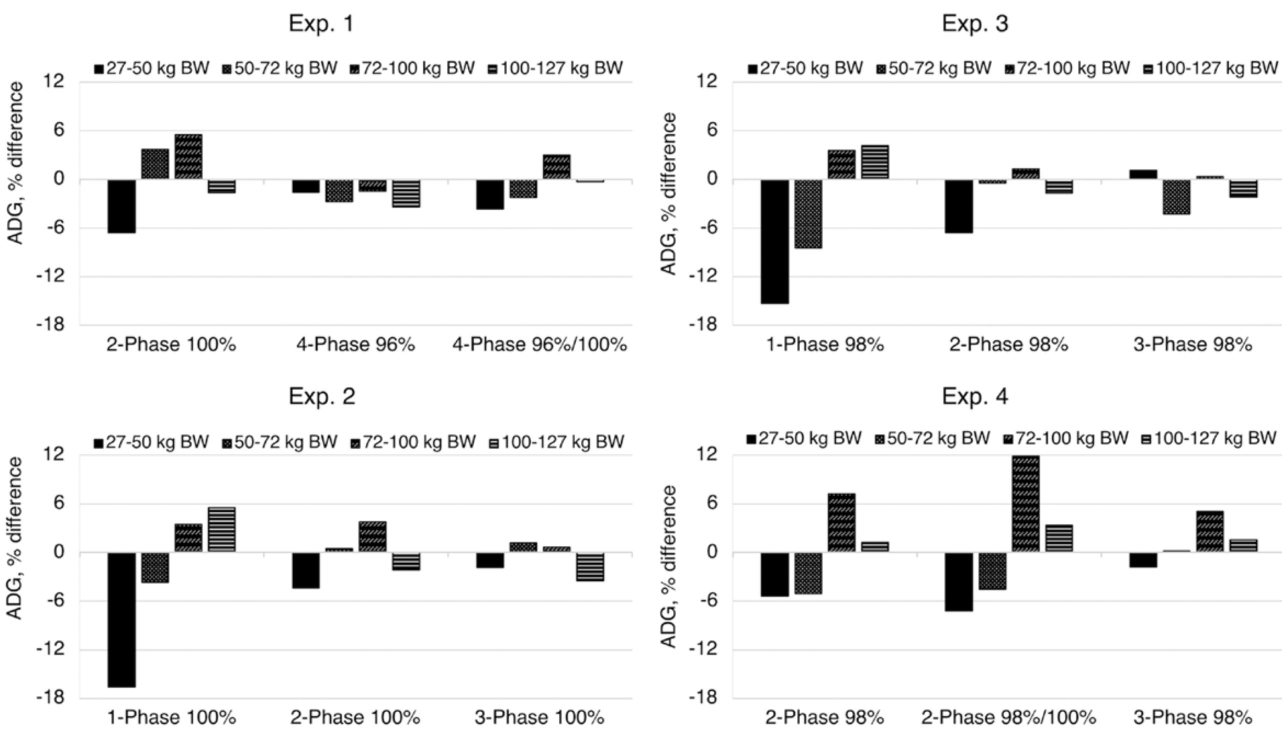

Figure 1. Relative intermediate performance of grow-finish pigs under feeding strategies based on number of dietary phases (one, two, three, and four dietary phases) and lysine specifications (96%, 98%, and 100% of estimated requirements for growth rate) in the grow-finish period. Relative difference in ADG determined by comparing within experiments the performance of the feeding strategies to the performance of the four-phase 100% (experiments 1 and 2) and four-phase 98% (experiments 3 and 4), which were considered as the standard-feeding strategies.

It appears feasible to simplify phase-feeding strategies to fewer dietary phases for grow-finish pigs without compromising growth performance and carcass characteristics. Simplification of phase-feeding strategies is an opportunity to exploit compensatory growth in grow-finish pigs as an approach to minimize the costs of diet formulation and optimize efficiency of feed utilization (Menegat et al., 2019). Moreover, simplification of phase-feeding strategies provides benefits in logistics of feed manufacture, delivery, and storage within the swine production system (Moore et al., 2012). From the feed manufacture standpoint, phase-feeding strategies with fewer diets provide an opportunity to improve feed mill efficiency, particularly with a continuous throughput pellet mill as longer larger tonnage runs improve mill efficiency. However, there is often an increase in nitrogen excretion in phase-feeding strategies with fewer dietary phases (Lee et al., 2000; Moore et al., 2012; Andretta et al., 2014). Although the nitrogen excretion in earlier phases is minimal due to Lys levels set below the requirement, the nitrogen excretion in subsequent phases increases due to Lys levels set above the requirement and, therefore, not being totally utilized for lean deposition (Han et al., 2000). Interestingly, O'Connell et al. (2005) suggest a similar nitrogen excretion is possible between single-phase and multi-phase-feeding strategies when the average Lys level is the same across the grow-finish period.

In conclusion, feeding strategies with Lys specifications set at 96% of estimated requirements compromise performance of grow-finish pigs unless Lys requirements are fully met in late finishing. Phase-feeding strategies provide performance advantages over feeding a single dietary phase throughout the grow-finish period. Simplification of feeding strategies from 4 to 3 or 2 dietary phases with Lys specifications at 98% to 100% of estimated requirements for growth rate does not compromise overall growth performance and carcass characteristics of grow-finish pigs from 27 to 127 kg BW. Although using feeding programs with fewer dietary phases and Lys set slightly below the requirements can compromise growth performance if initial BW and feed intake in the grow-finish period are lower than expected.

Conflict of interest statement

None declared.

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