Evaluation of standardized ileal digestible valine:lysine, total lysine:crude protein, and replacing fish meal, meat and bone meal, and poultry byproduct meal with crystalline amino acids on growth performance of nursery pigs from seven to twelve kilograms

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ABSTRACT: Five experiments were conducted to evaluate replacing fish meal, meat and bone meal, and poultry byproduct meal with crystalline AA for 7- to 12-kg pigs. In all experiments, pigs (PIC TR4 × 1050) were fed a common diet for 3 d postweaning, treatment diets for 14 d (d 0 to 14), and, again, a common diet for 14 d (d 14 to 28). Treatment diets were corn–soybean meal based and formulated to contain 1.30% standardized ileal digestible (SID) Lys. Experiment 1 evaluated replacing dietary fish meal with crystalline AA. For the 6 treatments, crystalline Lys, Met, Thr, Trp, Ile, Val, Gln, and Gly all increased to maintain minimum AA ratios as fish meal decreased (4.50, 3.60, 2.70, 1.80, and 0.90 to 0.00%). There was no difference in ADG, ADFI, or G:F among treatments, validating a low-CP, AA-fortified diet for subsequent experiments. Experiment 2 evaluated deleting crystalline AA from a low-CP, AA-fortified diet with 6 treatments: 1) a positive control similar to the diet validated in Exp. 1, 2) positive control with L-Ile deleted, 3) positive control with L-Trp deleted, 4) positive control with L-Val deleted, 5) positive control with L-Gln and L-Gly deleted, and 6) positive control with L-Ile, L-Trp, L-Val, L-Gln, and L-Gly deleted (NC). Pigs fed the positive control or Ile deleted diet had improved ($P < 0.05$) ADG and ADFI during d 0 to 14 compared with pigs fed diets with L-Trp or L-Val deleted or NC. Experiment 3 evaluated 6 treatments with total Lys:CP of 6.79, 6.92, 7.06, 7.20, 7.35, and 7.51%. Fish meal was adjusted as a source of dispensable N to achieve the target Lys:CP. There were no differences in growth performance among pigs fed different Lys:CP diets. Experiment 4 evaluated increasing SID Val:Lys with Val at 57.4, 59.9, 62.3, 64.7, 67.2, and 69.6% of Lys. Average daily gain and ADFI increased (quadratic, $P < 0.01$) and G:F improved (linear, $P = 0.02$) during d 0 to 14 as Val:Lys increased from 57.4 to 64.7%. Experiment 5 was a 2 × 3 factorial arrangement of treatments with main effects of low or high level of crystalline AA and 3 animal protein sources (fish meal, meat and bone meal, or poultry byproduct meal). Low- and high-crystalline AA diets contained 4.5 or 1% fish meal, 6 or 1.2% meat and bone meal, and 6 or 1% poultry byproduct meal, respectively. No AA × protein source interactions were observed. From d 0 to 14, no differences in growth performance among protein sources was found, whereas increasing crystalline AA improved ($P = 0.04$) ADG. In conclusion, crystalline AA can replace fish meal, meat and bone meal, and poultry byproduct meal when balanced for SID AA ratios of Met and Cys:Lys (58%), Thr:Lys (62%), Trp:Lys (16.5%), Val:Lys (65%), and Ile:Lys (52%).

Key words: crystalline amino acids, dispensable amino acid, pig, protein source, valine

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INTRODUCTION

Several experiments have been conducted to evaluate replacing animal protein with crystalline AA in the diet for nursery pigs. Low-protein AA-fortified diets have resulted in performance similar to that of the

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animal protein sources in several experiments (Frantz et al., 2005; Ratliff et al., 2005a; Bradley et al., 2008) but not in others (Kats et al., 1994; Davis et al., 1997; de Rodas et al., 1997). Much of the variation among experiments can be explained by the increased use of standardized ileal digestible (**SID**) ratios in diet formulation. Standardized ileal digestible AA estimates for most common feed ingredients are available, which allows for more accurate formulation to meet the AA requirements of the pigs (Stein et al., 2005, 2007). Decreases in performance from pigs fed low-CP, AA-fortified diets also may be a result of deficiencies in dispensable N, variation in lactose levels, or diets only formulated to the second or third limiting AA (Kats et al., 1994; de Rodas et al., 1997; Chung et al., 1999).

The objective of the following series of experiments was to evaluate the effect of replacing fish meal, meat and bone meal, and poultry byproduct meal with crystalline AA on growth performance of nursery pigs from 7 to 12 kg. To accomplish the overall objective, the subobjectives were to 1) establish a low-CP, AA-fortified diet that could be used to replace fish meal for subsequent experiments, 2) determine which AA were required in the low-CP, AA-fortified diet for optimal growth, 3) evaluate the maximum total Lys:CP required for growth, 4) determine the minimum SID Val:Lys requirement, and 5) validate crystalline AA as a replacement for fish meal, meat and bone meal, and poultry byproduct meal.

MATERIALS AND METHODS

All experimental procedures and animal care were approved by the Kansas State University Institutional Animal Care and Use Committee.

General

Similar protocols were used in all 5 experiments. Pigs (TR4 × 1050; PIC, Hendersonville, TN) were weaned at 19.5 ± 1.4 d of age and fed a common pelleted starter diet for 3 d. At weaning, pigs were allotted to mixed sex pens by sex and initial BW to achieve the same average weight for all pens. On d 3 after weaning, pens were allotted randomly to 1 of 6 dietary treatments; thus, d 3 after weaning was d 0 of the experiment. Treatments were balanced by sex on d 0 of the experiment to obtain equal number of barrows and gilts across all treatments. Each pen (1.22 by 1.52 m) contained a 4-hole dry self-feeder and a nipple waterer to provide ad libitum access to feed and water. All experiments were conducted at the Kansas State University Swine Teaching and Research Center.

A 2-phase diet series was used, with treatment diets fed from d 0 to 14 and a common diet fed from d 14 to 28. Treatment diets were corn–soybean meal based and contained 10% dried whey and 1% soy oil. In a previous study conducted in this facility, we determined that a SID Lys level of 1.30% was adequate for optimal ADG but inadequate for optimal G:F of pigs weighing 6.8 to 11.5 kg (Nemechek et al., 2012). Therefore, all diets from d 0 to 14 were formulated to be marginally deficient in SID Lys (1.30%). Following the experimental treatment diets, all pigs were switched to a common diet on d 14, and subsequent performance was monitored. From d 14 to 28, the diet for all the trials was a corn–soybean meal–based diet with no animal protein ingredients that was formulated to contain 1.26% SID Lys. Minimum nutrient specifications and SID AA digestibility coefficients used for all diet formulations were based on NRC (1998). All experimental diets were in meal form and were prepared at the Kansas State University Animal Science Feed Mill. A subsample of all experimental diets was collected and analyzed for dietary AA (Ajinomoto Heartland LLC, Chicago, IL) using HPLC as outlined by the AOAC International (2000). Pigs and feeders were weighed on d 0, 7, 14, 21, and 28 to calculate ADG, ADFI, and G:F.

Experiment 1

A total of 282 nursery pigs (initially 7.30 ± 0.08 kg BW) were used to evaluate the effects of replacing dietary fish meal with crystalline AA on growth performance. Each treatment had 5 replications with 7 pigs per pen and 2 replications with 6 pigs per pen. For the 6 dietary treatments, crystalline L-Lys, DL-Met, L-Thr, L-Trp, L-Ile, and L-Val were added to maintain minimum AA ratios at the expense of fish meal (Table 1). Dietary fish meal levels were 4.50, 3.60, 2.70, 1.80, 0.90, and 0.00%. Salt increased slightly with decreasing fish meal to maintain equal dietary Na among treatments. Also, increasing amounts of L-Gln and L-Gly were used in diets containing 3.60% or less fish meal to maintain a total Lys:CP of no more than 7:1%. Large, 1,270-kg batches of 4.50 and 0.00% fish meal diets were manufactured, and then they were blended at ratios of 80:20, 60:40, 40:60, and 20:80 to achieve the intermediate diets.

Experiment 2

A total of 294 nursery pigs (initially 6.88 ± 0.07 kg BW) were used to evaluate the effect of eliminating specific crystalline AA from a low-CP, AA-fortified diet based on growth performance. The experiment comprised 7 pigs per pen and 7 pens per treatment. The positive control diet contained L-Lys HCl, DL-Met, L-Thr, L-Ile, L-Trp, L-Val, L-Gln, and L-Gly and was a similar diet that was validated in Exp. 1, where all fish meal was re-

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

	Fish meal,[2] %						Common
Item	4.50	3.60	2.70	1.80	0.90	0.00	phase 2[3]
Ingredient, %							
Corn	56.58	56.82	57.07	57.32	57.56	57.81	65.70
Soybean meal (46.5% CP)	25.21	25.21	25.20	25.20	25.20	25.19	30.73
Spray-dried whey	10.00	10.00	10.00	10.00	10.00	10.00	–
Select menhaden fish meal[4]	4.50	3.60	2.70	1.80	0.90	–	–
Soybean oil	1.00	1.00	1.00	1.00	1.00	1.00	–
Monocalcium phosphate (21% P)	0.51	0.63	0.75	0.86	0.98	1.10	1.08
Limestone	0.55	0.62	0.69	0.76	0.83	0.90	0.95
Salt	0.30	0.31	0.32	0.33	0.34	0.35	0.35
Zinc oxide	0.25	0.25	0.25	0.25	0.25	0.25	–
Trace mineral premix[5]	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Vitamin premix[6]	0.25	0.25	0.25	0.25	0.25	0.25	0.25
L-Lys HCl	0.275	0.327	0.379	0.430	0.482	0.534	0.360
DL-Met	0.124	0.143	0.162	0.182	0.201	0.220	0.130
L-Thr	0.136	0.155	0.174	0.192	0.211	0.230	0.130
L-Trp	0.046	0.051	0.056	0.060	0.065	0.070	–
L-Ile	–	0.02	0.04	0.06	0.08	0.10	–
L-Val	0.037	0.062	0.086	0.111	0.135	0.160	–
L-Gln	–	0.16	0.32	0.48	0.64	0.80	–
L-Gly	–	0.16	0.32	0.48	0.64	0.80	–
Phytase[7]	0.085	0.085	0.085	0.085	0.085	0.085	0.165
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Analyzed nutrient composition of diets, % (as-fed basis)							
CP	20.3	20.9	19.6	19.9	20.1	18.8	–
Lys	1.25	1.19	1.24	1.25	1.30	1.19	–
Ile	0.81	0.73	0.81	0.74	0.73	0.76	–
Leu	1.50	1.44	1.47	1.47	1.41	1.39	–
Met	0.37	0.37	0.39	0.38	0.39	0.38	–
Met + Cys	0.60	0.64	0.65	0.62	0.60	0.64	–
Thr	0.81	0.90	0.86	0.89	0.85	0.83	–
Trp	0.29	0.32	0.33	0.32	0.32	0.28	–
Val	0.88	0.86	0.86	0.86	0.88	0.85	–
Arg	1.28	1.25	1.21	1.26	1.30	1.10	–
His	0.47	0.47	0.45	0.43	0.40	0.40	–
Phe	0.87	0.86	0.85	0.82	0.81	0.81	–
Phe + Tyr	1.45	1.44	1.41	1.38	1.34	1.31	–
Gln	3.40	3.31	3.29	3.31	3.36	3.45	–
Gly	0.90	1.03	1.10	1.06	1.25	1.50	–
Calculated analysis							
SID[8] Lys, %	1.30	1.30	1.30	1.30	1.30	1.30	1.26
ME, kcal/kg	3,369	3,366	3,362	3,358	3,355	3,351	3,314
SID Lys:ME, g/Mcal	3.86	3.86	3.87	3.87	3.87	3.88	3.80
CP, %	21.1	20.9	20.8	20.6	20.5	20.3	20.8
Total Lys:CP, %	6.78	6.84	6.88	6.89	6.93	7.00	6.68
Ca, %	0.72	0.72	0.72	0.72	0.72	0.72	0.69
P, %	0.65	0.65	0.64	0.64	0.64	0.64	0.62
Available P, %	0.47	0.47	0.47	0.47	0.47	0.47	0.42

[1]A total of 282 nursery pigs (PIC TR4 × 1050; PIC, Hendersonville, TN) were used in a 28-d trial to evaluate the effects of replacing fish meal with crystalline AA on growth performance.

[2]Treatment diets were fed from d 0 to 14.

[3]Common diet was fed from d 14 to 28.

[4]Omega Protein Corp., Houston, TX.

[5]Trace mineral premix provided per kilogram of complete feed: 16.5 mg of Cu from $CuSO_4 \cdot 5H_20$, 0.30 mg of I as $C_2H_2(NH_2)_2 \cdot 2HI$, 165 mg of Fe as $FeSO_4H_2O$, 39.7 mg of Mn as $MnSO_4 \cdot H_2O$, 0.30 mg of Se as Na_2SeO_3, and 165 mg of Zn as $ZnSO_4$.

[6]Vitamin premix provided per kilogram of complete feed: 11,023 IU of vitamin A, 1,377 IU of vitamin D, 44.1 IU of vitamin E, 4.4 mg of vitamin K, 0.04 mg of vitamin B_{12}, 50.0 mg of niacin, 27.6 mg of pantothenic acid, and 8.3 mg of riboflavin.

[7]Phyzyme 600 (Danisco Animal Nutrition, St. Louis, MO) provided 509 phytase units/kg, with a release of 0.10% available P.

[8]SID = standardized ileal digestible.

placed with crystalline AA (Table 2). Standardized ileal digestible AA ratios of the positive control diet relative to Lys were 60% Ile, 58% Met and Cys, 64% Thr, 20% Trp, and 70% Val and total Lys:CP of 6.95%. The 6 treatments were 1) positive control, 2) positive control with L-Ile deleted from the diet (52% SID Ile:Lys), 3) positive control with L-Trp deleted (15% SID Trp:Lys), 4) positive control with L-Val deleted (57% SID Val:Lys), 5) positive control with L-Gln and L-Gly deleted (7.51% total Lys:CP), and 6) positive control with L-Ile, L-Trp, L-Val, L-Gln, and L-Gly removed from the diet. Treatment 6 served as the negative control and contained SID AA ratios of 52% Ile:Lys, 15% Trp:Lys, 57% Val:Lys, and 7.60% total Lys:CP.

Experiment 3

A total of 282 nursery pigs (initially 7.23 ± 0.07 kg BW) were used to evaluate the effects of total Lys:CP on growth performance, using fish meal as a source of nonessential N. Each treatment had 5 replications with 7 pigs per pen and 2 replications with 6 pigs per pen. The 6 total Lys:CP were 6.79, 6.92, 7.06, 7.20, 7.35, and 7.51% (Table 3). All diets were formulated to 1.30% SID Lys. Crystalline L-Lys, DL-Met, L-Thr, L-Trp, and L-Val all increased as fish meal decreased to maintain minimum AA ratios of 58% Met and Cys:Lys, 64% Thr:Lys, 20% Trp:Lys, 52% Ile:Lys, and 70% Val:Lys. Large, 1,270-kg batches of the 6.79 and 7.51% total Lys:CP diets were manufactured, and then they were blended at ratios of 80:20, 60:40, 40:60, and 20:80 to achieve the intermediate diets.

Experiment 4

A total of 294 nursery pigs (initially 6.84 ± 0.05 kg BW) were used to evaluate the effects of increasing SID Val:Lys on growth performance, with 7 pigs per pen and 7 pens per treatment. The 6 dietary treatments contained Val at 57.4, 59.9, 62.3, 64.7, 67.2, and 69.6% of Lys (Table 4). These ratios were achieved by increasing crystalline L-Val and decreasing corn starch in equal amounts. Large, 1,270-kg batches of the 57.4 and 69.6% Val diets were manufactured, and they were then blended at ratios of 80:20, 60:40, 40:60, and 20:80 to achieve the intermediate diets.

Experiment 5

A total of 282 nursery pigs (initially 6.59 ± 0.06 kg BW) were used to evaluate the effects of replacing high amounts of fish meal, meat and bone meal, and poultry byproduct meal with crystalline AA on growth performance. Each treatment had 5 replications with 7 pigs per pen and 2 replications with 6 pigs per pen. Experimental treatments were arranged in a 2 × 3 factorial (Table 5). Pens were assigned to 1 of 3 dietary animal protein sources including select menhaden fish meal (4.50 vs. 1.00%), porcine meat and bone meal (6.00 vs. 1.20%), or pet food-grade poultry byproduct meal (6.00 vs. 1.05%). Each animal protein source with a high or low inclusion rate was supplemented with a low or high level of crystalline AA. Fish meal, meat and bone meal, or poultry byproduct meal was included in the high-crystalline AA diets accordingly to ensure a total Lys:CP was not greater than 7.36%. Appropriate amounts of crystalline AA were added to diets to maintain SID Ile, Met + Cys, Thr, Trp, and Val to 52, 58, 62, 16.4, and 65% of Lys.

Statistical Analysis

All experiments were analyzed as a completely randomized design with the pen as the experimental unit. Data from each experiment were analyzed using the PROC MIXED procedure of SAS (SAS Inst. Inc., Cary, NC). Experiments 1, 3, and 4 were analyzed using orthogonal polynomial contrasts to determine the effect of decreasing dietary fish meal, increasing dietary total Lys:CP, and increasing SID Val:Lys, respectively. For SID Val:Lys, breakpoint analysis described by Robbins et al. (2006) was used to determine estimates of requirements. Analysis of variance was performed for Exp. 2 and 5. Experiment 5 was analyzed as a 2 × 3 factorial with 2 crystalline AA levels and 3 animal protein sources, and differences between treatments were determined using the PDIFF. Significant differences for all experiments were declared at $P < 0.05$ and trends were declared at $P < 0.10$.

RESULTS AND DISCUSSION

Experiment 1

Analyzed AA levels for experimental diets are shown in Table 1. Analyzed concentrations were numerically lower than formulated concentrations but are within acceptable limits for analytical variation according to the Association of American Feed Control Officials (2005). From d 0 to 14 (experimental treatment period), there was no difference in ADG, ADFI, or G:F as dietary fish meal decreased and crystalline AA increased (Table 6). From d 14 to 28 (common diet period), there were no differences among treatments for ADG or G:F, but there was a quadratic trend ($P = 0.09$) for ADFI as dietary fish meal decreased.

Overall (d 0 to 28), there were no differences in ADG or ADFI. As dietary fish meal increased, feed efficiency improved (quadratic, $P = 0.04$) as a result of increases in G:F at the intermediate fish meal levels (2.70 and 1.80%).

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

Item	Positive control	Crystalline AA removed from the diet: Ile	Trp	Val	Gly/Gln	Negative control	Common phase 2
Ingredient, %							
Corn	58.14	58.14	58.14	58.14	58.14	58.14	65.70
Soybean meal (46.5% CP)	25.20	25.20	25.20	25.20	25.20	25.20	30.73
Spray-dried whey	10.00	10.00	10.00	10.00	10.00	10.00	–
Corn starch	–	0.10	0.07	0.16	1.26	1.59	–
Soybean oil	1.00	1.00	1.00	1.00	1.00	1.00	–
Monocalcium phosphate (21% P)	1.10	1.10	1.10	1.10	1.10	1.10	1.08
Limestone	0.90	0.90	0.90	0.90	0.90	0.90	0.95
Salt	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Zinc oxide	0.25	0.25	0.25	0.25	0.25	0.25	–
Trace mineral premix[3]	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Vitamin premix[4]	0.25	0.25	0.25	0.25	0.25	0.25	0.25
L-Lys HCl	0.533	0.533	0.533	0.533	0.533	0.533	0.360
DL-Met	0.220	0.220	0.220	0.220	0.220	0.220	0.130
L-Thr	0.230	0.230	0.230	0.230	0.230	0.230	0.130
L-Trp	0.070	0.070	–	0.070	0.070	–	–
L-Ile	0.100	–	0.100	0.100	0.100	–	–
L-Val	0.160	0.160	0.160	–	0.160	–	–
L-Gln	0.630	0.630	0.630	0.630	–	–	–
L-Gly	0.630	0.630	0.630	0.630	–	–	–
Phytase 600[5]	0.085	0.085	0.085	0.085	0.085	0.085	0.165
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Analyzed nutrient composition of diets, % (as-fed basis)							
CP	19.3	20.1	19.5	20.6	18.9	18.3	–
Lys	1.16	1.26	1.20	1.28	1.23	1.30	–
Ile	0.72	0.68	0.73	0.81	0.76	0.72	–
Leu	1.39	1.41	1.37	1.45	1.42	1.41	–
Met	0.37	0.39	0.38	0.39	0.39	0.38	–
Met + Cys	0.61	0.64	0.62	0.65	0.64	0.63	–
Thr	0.77	0.80	0.78	0.84	0.79	0.77	–
Trp	0.27	0.26	0.23	0.27	0.20	0.24	–
Val	0.84	0.89	0.88	0.80	0.87	0.78	–
Arg	1.23	1.32	1.24	1.32	1.33	1.29	–
His	0.40	0.40	0.40	0.42	0.40	0.39	–
Phe	0.77	0.79	0.79	0.81	0.79	0.75	–
Phe + Tyr	1.27	1.31	1.31	1.35	1.33	1.29	–
Gln	3.21	3.42	3.37	3.46	3.08	2.82	–
Gly	1.09	1.18	1.14	1.17	0.72	0.60	–
Calculated analysis							
SID[6] Lys, %	1.30	1.30	1.30	1.30	1.30	1.30	1.26
ME, kcal/kg	3,342	3,342	3,342	3,342	3,342	3,342	3,314
SID Lys:ME, g/Mcal	3.89	3.89	3.89	3.89	3.87	3.88	3.80
CP, %	20.4	20.4	20.4	20.3	18.9	18.7	20.8
Total Lys:CP, %	6.96	6.96	6.96	7.00	7.51	7.60	6.68
Ca, %	0.72	0.72	0.72	0.72	0.72	0.72	0.69
P, %	0.64	0.64	0.64	0.64	0.64	0.64	0.62
Available P, %	0.47	0.47	0.47	0.47	0.47	0.47	0.42

[1]A total of 294 nursery pigs (PIC TR4 × 1050; PIC, Hendersonville, TN) were used in a 28-d trial to evaluate the effects deleting crystalline AA from a low-CP, AA-fortified diet.

[2]Treatment diets were fed from d 0 to 14 and a common diet was fed from d 14 to 28.

[3]Trace mineral premix provided per kilogram of complete feed: 16.5 mg of Cu from $CuSO_4 \cdot 5H_20$, 0.30 mg of I as $C_2H_2(NH_2)_2 \cdot 2HI$, 165 mg of Fe as $FeSO_4H_2O$, 39.7 mg of Mn as $MnSO_4 \cdot H_2O$, 0.30 mg of Se as Na_2SeO_3, and 165 mg of Zn as $ZnSO_4$.

[4]Vitamin premix provided per kilogram of complete feed: 11,023 IU of vitamin A, 1,377 IU of vitamin D, 44.1 IU of vitamin E, 4.4 mg of vitamin K, 0.04 mg of vitamin B_{12}, 50.0 mg of niacin, 27.6 mg of pantothenic acid, and 8.3 mg of riboflavin.

[5]Phyzyme 600 (Danisco Animal Nutrition, St. Louis, MO) provided 509 phytase units/kg, with a release of 0.10% available P.

[6]SID = standardized ileal digestible.

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

Item	Total Lys:CP,[2] %						Common phase 2[3]
	6.79	6.92	7.06	7.20	7.35	7.51	
Ingredient, %							
Corn	56.58	57.19	57.79	58.40	59.01	59.61	65.70
Soybean meal (46.5% CP)	25.21	25.18	25.16	25.14	25.11	25.09	30.73
Spray-dried whey	10.00	10.00	10.00	10.00	10.00	10.00	–
Select menhaden fish meal[4]	4.50	3.60	2.70	1.80	0.90	–	–
Soybean oil	1.00	1.00	1.00	1.00	1.00	1.00	–
Monocalcium phosphate (21% P)	0.51	0.63	0.75	0.86	0.98	1.10	1.08
Limestone	0.55	0.62	0.69	0.76	0.83	0.90	0.95
Salt	0.30	0.31	0.32	0.33	0.34	0.35	0.35
Zinc oxide	0.25	0.25	0.25	0.25	0.25	0.25	–
Trace mineral premix[5]	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Vitamin premix[6]	0.25	0.25	0.25	0.25	0.25	0.25	0.25
L-Lys HCl	0.275	0.327	0.378	0.430	0.481	0.533	0.360
DL-Met	0.124	0.143	0.162	0.182	0.201	0.220	0.130
L-Thr	0.136	0.155	0.174	0.192	0.211	0.230	0.130
L-Trp	0.046	0.051	0.056	0.060	0.065	0.070	–
L-Val	0.037	0.062	0.086	0.111	0.135	0.160	–
Phytase[7]	0.085	0.085	0.085	0.085	0.085	0.085	0.165
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Analyzed nutrient composition of diets, % (as-fed basis)							
CP	21.1	19.4	19.0	20.5	18.2	17.5	–
Lys	1.43	1.35	1.29	1.38	1.26	1.05	–
Ile	0.77	0.73	0.70	0.76	0.70	0.63	–
Leu	1.55	1.50	1.46	1.53	1.44	1.37	–
Met	0.45	0.43	0.41	0.45	0.41	0.40	–
Met + Cys	0.74	0.72	0.69	0.75	0.70	0.66	–
Thr	0.94	0.93	0.89	0.95	0.87	0.77	–
Trp	0.30	0.22	0.26	0.29	0.28	0.26	–
Val	0.99	0.96	0.93	0.98	0.90	0.81	–
Arg	1.47	1.39	1.38	1.11	1.20	1.29	–
His	0.47	0.46	0.44	0.44	0.43	0.41	–
Phe	0.90	0.89	0.82	0.83	0.80	0.80	–
Phe + Tyr	1.49	1.45	1.37	1.37	1.34	1.29	–
Gln	3.07	3.13	3.26	2.98	2.87	2.90	–
Gly	0.92	0.72	0.77	0.68	0.67	0.64	–
Calculated analysis							
SID[8] Lys, %	1.30	1.30	1.30	1.30	1.30	1.30	1.26
ME, kcal/kg	3,369	3,365	3,360	3,355	3,351	3,346	3,314
SID Lys:ME, g/Mcal	3.86	3.86	3.87	3.87	3.88	3.89	3.80
CP, %	21.1	20.6	20.2	19.8	19.4	18.9	20.8
Ca, %	0.72	0.72	0.72	0.72	0.72	0.72	0.69
P, %	0.65	0.65	0.65	0.65	0.64	0.64	0.62
Available P, %	0.47	0.47	0.47	0.47	0.47	0.47	0.42

[1]A total of 282 nursery pigs (PIC TR4 × 1050; PIC, Hendersonville, TN) were used in a 28-d trial to evaluate the effects of total Lys:CP on growth performance.

[2]Treatment diets were fed from d 0 to 14.

[3]Common diet was fed from d 14 to 28.

[4]Omega Protein Corp., Houston, TX.

[5]Trace mineral premix provided per kilogram of complete feed: 16.5 mg of Cu from $CuSO_4 \cdot 5H_20$, 0.30 mg of I as $C_2H_2(NH_2)_2 \cdot 2HI$, 165 mg of Fe as $FeSO_4H_2O$, 39.7 mg of Mn as $MnSO_4 \cdot H_2O$, 0.30 mg of Se as Na_2SeO_3, and 165 mg of Zn as $ZnSO_4$.

[6]Vitamin premix provided per kilogram of complete feed: 11,023 IU of vitamin A, 1,377 IU of vitamin D, 44.1 IU of vitamin E, 4.4 mg of vitamin K, 0.04 mg of vitamin B_{12}, 50.0 mg of niacin, 27.6 mg of pantothenic acid, and 8.3 mg of riboflavin.

[7]Phyzyme 600 (Danisco Animal Nutrition, St. Louis, MO) provided 509 phytase units/kg, with a release of 0.10% available P.

[8]SID = standardized ileal digestible.

Table 4. Composition of diets, Exp. 4 (as-fed basis)[1]

Item	Standardized ileal digestible (SID) Val:Lys,[2] %						Common phase 2[3]
	57.4	59.9	62.3	64.7	67.2	69.6	
Ingredient, %							
Corn	58.25	58.25	58.25	58.25	58.25	58.25	65.70
Soybean meal (46.5% CP)	25.19	25.19	25.19	25.19	25.19	25.19	30.73
Spray-dried whey	10.00	10.00	10.00	10.00	10.00	10.00	–
Corn starch	0.160	0.128	0.096	0.064	0.032	–	–
Soybean oil	1.00	1.00	1.00	1.00	1.00	1.00	–
Monocalcium phosphate (21% P)	1.10	1.10	1.10	1.10	1.10	1.10	1.08
Limestone	0.90	0.90	0.90	0.90	0.90	0.90	0.95
Salt	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Zinc oxide	0.25	0.25	0.25	0.25	0.25	0.25	–
Trace mineral premix[4]	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Vitamin premix[5]	0.25	0.25	0.25	0.25	0.25	0.25	0.25
L-Lys HCl	0.533	0.533	0.533	0.533	0.533	0.533	0.360
DL-Met	0.220	0.220	0.220	0.220	0.220	0.220	0.130
L-Thr	0.230	0.230	0.230	0.230	0.230	0.230	0.130
L-Trp	0.070	0.070	0.070	0.070	0.070	0.070	–
L-Val	–	0.032	0.064	0.096	0.128	0.160	–
L-Gln	0.630	0.630	0.630	0.630	0.630	0.630	–
L-Gly	0.630	0.630	0.630	0.630	0.630	0.630	–
Phytase[6]	0.085	0.085	0.085	0.085	0.085	0.085	0.165
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Analyzed nutrient composition of diets, % (as-fed basis)							
CP	19.0	18.3	18.9	19.4	19.0	19.2	–
Lys	1.18	1.18	1.14	1.21	1.13	1.16	–
Ile	0.69	0.69	0.67	0.70	0.66	0.67	–
Leu	1.42	1.43	1.39	1.45	1.35	1.38	–
Met	0.38	0.40	0.38	0.39	0.39	0.40	–
Met + Cys	0.64	0.66	0.64	0.66	0.64	0.66	–
Thr	0.86	0.86	0.85	0.88	0.81	0.82	–
Trp	0.29	0.31	0.35	0.33	0.30	0.29	–
Val	0.79	0.82	0.82	0.87	0.88	0.90	–
Arg	1.14	1.15	1.05	1.27	1.10	1.22	–
His	0.44	0.43	0.44	0.46	0.40	0.41	–
Phe	0.78	0.80	0.76	0.77	0.81	0.81	–
Phe + Tyr	1.28	1.32	1.28	1.26	1.34	1.35	–
Gln	3.28	3.65	3.22	3.63	3.59	3.49	–
Gly	1.22	1.09	1.29	1.27	1.17	1.13	–
Calculated analysis							
SID Lys, %	1.30	1.30	1.30	1.30	1.30	1.30	1.26
ME, kcal/kg	3,342	3,342	3,342	3,342	3,342	3,342	3,314
SID Lys:ME, g/Mcal	3.89	3.89	3.89	3.89	3.89	3.89	3.80
CP, %	20.2	20.3	20.3	20.3	20.3	20.4	20.8
Ca, %	0.72	0.72	0.72	0.72	0.72	0.72	0.69
P, %	0.64	0.64	0.64	0.64	0.64	0.64	0.62
Available P, %	0.47	0.47	0.47	0.47	0.47	0.47	0.42

[1]A total of 294 nursery pigs (PIC TR4 × 1050; PIC, Hendersonville, TN) were used in a 28-d trial to evaluate the effects of SID Val:Lys on growth performance.

[2]Treatment diets were fed from d 0 to 14.

[3]Common diet was fed from d 14 to 28.

[4]Trace mineral premix provided per kilogram of complete feed: 16.5 mg of Cu from $CuSO_4 \cdot 5H_20$, 0.30 mg of I as $C_2H_2(NH_2)_2 \cdot 2HI$, 165 mg of Fe as $FeSO_4H_2O$, 39.7 mg of Mn as $MnSO_4 \cdot H_2O$, 0.30 mg of Se as Na_2SeO_3, and 165 mg of Zn as $ZnSO_4$.

[5]Vitamin premix provided per kilogram of complete feed: 11,023 IU of vitamin A, 1,377 IU of vitamin D, 44.1 IU of vitamin E, 4.4 mg of vitamin K, 0.04 mg of vitamin B_{12}, 50.0 mg of niacin, 27.6 mg of pantothenic acid, and 8.3 mg of riboflavin.

[6]Phyzyme 600 (Danisco Animal Nutrition, St. Louis, MO) provided 509 phytase units/kg, with a release of 0.10% available P.

Table 5. Composition of diets, Exp. 5 (as-fed basis)[1]

	Phase 1[2]						
	Crystalline AA level: Low			Crystalline AA level: High			
	Protein source						
Item	Fish meal	Meat and bone meal	Poultry byproduct meal	Fish meal	Meat and bone meal	Poultry byproduct meal	Common phase 2[3]
Ingredient, %							
Corn	56.71	56.03	54.41	59.01	59.06	59.03	65.70
Soybean meal (46.5% CP)	25.20	25.20	25.20	25.27	25.20	25.20	30.73
Spray-dried whey	10.00	10.00	10.00	10.00	10.00	10.00	–
Select menhaden fish meal[4]	4.50	–	–	1.00	–	–	–
Meat and bone meal	–	6.00	–	–	1.20	–	–
Poultry byproduct meal	–	–	6.00	–	–	1.00	–
Soybean oil	1.00	1.00	1.00	1.00	1.00	1.00	–
Monocalcium phosphate (21% P)	0.50	–	0.40	1.00	0.85	1.00	1.08
Limestone	0.55	–	0.40	0.75	0.65	0.75	0.95
Salt	0.30	0.30	0.30	0.30	0.30	0.30	0.35
Zinc oxide	0.25	0.25	0.25	0.25	0.25	0.25	–
Trace mineral premix[5]	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Vitamin premix[6]	0.25	0.25	0.25	0.25	0.25	0.25	0.25
L-Lys HCl	0.275	0.385	0.310	0.470	0.500	0.495	0.360
DL-Met	0.125	0.180	0.140	0.200	0.205	0.200	0.130
L-Thr	0.100	0.140	0.100	0.175	0.195	0.190	0.130
L-Trp	–	0.010	–	0.018	0.020	0.020	–
L-Val	–	0.015	–	0.070	0.080	0.075	–
Phytase[7]	0.085	0.085	0.085	0.085	0.085	0.085	0.165
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Analyzed nutrient composition of diets, % (as-fed basis)							
CP	19.0	20.1	19.7	18.9	18.0	18.9	–
Lys	1.24	1.18	1.20	1.15	1.24	1.18	–
Ile	0.82	0.78	0.87	0.69	0.72	0.73	–
Leu	1.55	1.58	1.58	1.49	1.50	1.52	–
Met	0.38	0.43	0.41	0.45	0.43	0.38	–
Met + Cys	0.59	0.61	0.66	0.67	0.65	0.62	–
Thr	0.77	0.76	0.80	0.77	0.76	0.82	–
Trp	0.28	0.31	0.26	0.25	0.27	0.26	–
Val	0.92	0.91	0.96	0.90	0.84	0.89	–
Arg	1.26	1.23	1.52	1.32	1.21	1.25	–
His	0.60	0.46	0.47	0.42	0.51	0.43	–
Phe	0.88	0.87	1.00	0.80	0.87	0.81	–
Phe + Tyr	1.46	1.45	1.70	1.33	1.50	1.32	–
Gln	3.08	3.04	3.14	2.97	2.96	2.92	–
Gly	0.86	1.05	1.01	0.64	0.76	0.76	–
Calculated analysis							
SID[9] Lys, %	1.30	1.30	1.30	1.30	1.30	1.30	1.26
ME, kcal/kg	3,369	3,366	3,362	3,358	3,355	3,351	3,314
SID Lys:ME, g/Mcal	3.86	3.89	3.89	3.88	3.88	3.88	3.80
CP, %	21.0	21.4	22.4	19.4	19.4	19.4	20.8
Total Lys:CP, %	6.82	6.78	6.53	7.35	7.36	7.36	6.68
Ca, %	0.71	0.78	0.71	0.70	0.70	0.70	0.69
P, %	0.65	0.70	0.65	0.65	0.65	0.65	0.62
Available P, %	0.47	0.50	0.47	0.48	0.47	0.47	0.42

[1]A total of 282 nursery pigs (PIC TR4 × 1050; PIC, Hendersonville, TN) were used in a 28-d trial to evaluate the effects of replacing high amounts of fish meal, meat and bone meal, and poultry byproduct meal with crystalline AA on growth performance.

[2]Treatment diets were fed from d 0 to 14.

[3]Common diet was fed from d 14 to 28.

[4]Omega Protein Corp., Houston, TX.

[5]Trace mineral premix provided per kilogram of complete feed: 16.5 mg of Cu from $CuSO_4{\cdot}5H_20$, 0.30 mg of I as $C_2H_2(NH_2)_2{\cdot}2HI$, 165 mg of Fe as $FeSO_4H_2O$, 39.7 mg of Mn as $MnSO_4{\cdot}H_2O$, 0.30 mg of Se as Na_2SeO_3, and 165 mg of Zn as $ZnSO_4$.

[6]Vitamin premix provided per kilogram of complete feed: 11,023 IU of vitamin A, 1,377 IU of vitamin D, 44.1 IU of vitamin E, 4.4 mg of vitamin K, 0.04 mg of vitamin B_{12}, 50.0 mg of niacin, 27.6 mg of pantothenic acid, and 8.3 mg of riboflavin.

[7]Phyzyme 600 (Danisco Animal Nutrition, St. Louis, MO) provided 509 phytase units/kg, with a release of 0.10% available P.

[8]SID = standardized ileal digestible.

Table 6. Evaluation of replacing fish meal with crystalline AA on growth performance in nursery pig diets (Exp. 1)[1,2]

	Fish meal, %							*P*-value	
Item	4.50	3.60	2.70	1.80	0.90	0.00	SEM	Linear	Quadratic
BW, kg									
d 0	7.27	7.31	7.26	7.34	7.33	7.29	0.08	0.68	0.70
d 14	12.53	12.52	12.71	12.63	12.65	12.62	0.18	0.64	0.66
d 28	20.64	20.26	20.72	20.01	20.51	20.29	0.30	0.50	0.74
d 0 to 14									
ADG, g	376	372	389	378	380	380	11	0.71	0.73
ADFI, g	528	517	537	525	531	546	16	0.38	0.62
G:F	0.713	0.720	0.730	0.719	0.715	0.698	0.018	0.52	0.29
d 14 to 28									
ADG, g	579	553	579	527	562	548	13	0.11	0.45
ADFI, g	953	906	944	860	935	919	19	0.31	0.09
G:F	0.608	0.610	0.614	0.614	0.601	0.596	0.009	0.25	0.22
d 0 to 28									
ADG, g	477	462	484	452	471	464	9	0.34	0.71
ADFI, g	741	712	739	693	733	733	14	0.86	0.16
G:F	0.645	0.650	0.654	0.653	0.642	0.634	0.007	0.14	0.04

[1]A total of 282 nursery pigs (PIC TR4 × 1050; PIC, Hendersonville, TN) were used in a 28-d trial to evaluate the effects of replacing fish meal with crystalline AA on growth performance. Values represent the means of 7 pens per treatment.

[2]Treatment diets were fed from d 0 to 14 and a common diet fed from d 14 to 28.

Data from this trial indicate that crystalline AA can be used to replace fish meal in diets for 7- to 12-kg pigs, which is in agreement with 3 studies reported by Ratliff et al. (2005a) that used dietary fish meal ranging from 6 to 0% and increasing concentrations of L-Lys HCl, L-Thr, DL-Met, L-Trp, L-Ile, and L-Val as dietary fish meal decreased.

Bradley et al. (2008) conducted a similar study evaluating the effect of replacing fish meal with crystalline AA in phase 1 and 2 nursery diets. Fish meal ranged from 8 to 0% and 6 to 0% during phases 1 and 2, respectively. The researchers found no differences in ADG or ADFI during both phases, which is consistent with the current study; however, as dietary fish meal decreased and crystalline AA increased, G:F decreased linearly. Bradley et al. (2008) did not include L-Trp or additional sources of dispensable N in the diets, whereas results of Exp. 2 reported herein indicated that both are required in low-CP, AA-fortified nursery diets for optimal growth. Numerical differences reported by Bradley et al. (2008) in ADG and ADFI may have resulted from a moderate deficiency in Trp or dispensable N, which may explain the discrepancy in G:F between studies.

The present study, Bradley et al. (2008), and Ratliff et al. (2005a) agree that crystalline AA, when balanced for minimum SID AA ratios, can be used to replace fish meal in diets for 6.8- to 11.3-kg pigs. These data established a low-CP, AA-fortified diet that could be used in our subsequent experiments.

Experiment 2

Analyzed AA levels for experimental diets are shown in Table 2. Analyzed concentrations were lower than formulated concentrations but are within acceptable limits for analytical variation according to the Association of American Feed Control Officials (2005). The results of AA analysis were in agreement with the design of the experiment, confirming that the specific crystalline AA were removed from the respective diets.

From d 0 to 14 (experimental treatment period), pigs fed the diet containing no added crystalline Ile had no difference in ADG, ADFI, and G:F compared to pigs fed the positive control but had increased ($P < 0.05$) ADG compared with the pigs fed the other 4 diets (Table 7). Pigs fed the diets with deleted L-Trp or L-Val had decreased ($P < 0.05$) ADG and ADFI compared with the pigs fed the positive control diet. Pigs fed the diet without L-Gln and L-Gly were intermediate. As expected, feeding the negative control diet resulted in decreased ($P < 0.05$) ADG and ADFI. There were no differences in G:F among any of the treatments during the first period, indicating that the response to ADG among treatments was driven primarily by ADFI. From d 14 to 28, when the common diet was fed, for unknown reasons, pigs fed the diet with L-Ile deleted during the previous period had decreased ($P < 0.05$) ADG and poorer ($P < 0.05$) G:F compared with the positive control. Pigs in the other treatment groups had no difference in ADG and G:F compared to the positive control. There were no differences in ADFI. Overall (d 0 to 28), because of the decrease in ADG from d 0 to 14, pigs fed the negative control diet or diets without L-Trp or L-Val had decreased ($P < 0.05$) ADG compared with pigs fed the positive control. Pigs fed the negative control had decreased ($P < 0.04$) ADFI compared with pigs fed the positive control. There was no difference in G:F for the overall study.

Table 7. Effects of deleting crystalline AA from low-CP, AA-fortified diets on growth performance in nursery pigs (Exp. 2)[1,2]

		Crystalline AA removed from the diet					
Item	Positive control[3]	Ile	Trp	Val	Gly/Gln	Negative control[4]	SEM
BW, kg							
d 0	6.89	6.89	6.87	6.88	6.88	6.86	0.07
d 14	11.14[bc]	11.36[c]	10.45[a]	10.32[a]	10.76[ab]	10.28[a]	0.21
d 28	18.65[b]	18.01[ab]	17.51[a]	17.63[a]	18.18[ab]	17.60[a]	0.36
d 0 to 14							
ADG, g	303[bc]	320[c]	256[a]	246[a]	277[ab]	244[a]	13
ADFI, g	420[b]	433[b]	367[a]	345[a]	390[ab]	345[a]	16
G:F	0.723	0.738	0.697	0.711	0.709	0.703	0.016
d 14 to 28							
ADG, g	536[b]	475[a]	504[ab]	522[b]	530[b]	523[b]	14
ADFI, g	854	801	807	831	862	816	25
G:F	0.630[b]	0.593[a]	0.626[b]	0.629[b]	0.616[ab]	0.642[b]	0.011
d 0 to 28							
ADG, g	420[b]	397[ab]	380[a]	384[a]	403[ab]	384[a]	12
ADFI, g	637[b]	617[ab]	587[ab]	588[ab]	626[ab]	581[a]	19
G:F	0.661	0.644	0.648	0.653	0.645	0.660	0.010

[a,b,c]Within a row, means without a common superscript differ ($P < 0.05$).

[1]A total of 294 nursery pigs (PIC TR4 × 1050; PIC, Hendersonville, TN) were used in a 28-d growth trial to evaluate the deletion of crystalline AA from a low-CP, AA-fortified diet on growth performance. Values represent the means of 7 pens per treatment.

[2]Treatment diets were fed from d 0 to 14 and a common diet fed from d 14 to 28.

[3]Contained crystalline Lys, Met, Thr, Ile, Trp, Val, Gln, and Gly.

[4]Positive control diet with removal of crystalline Ile, Trp, Val, Gln, and Gly.

The positive control diet used during the first period was previously shown to provide adequate AA for optimal growth in nursery pigs from 6.8 to 11.3 kg in Exp. 1. The present data showed similar performance between the positive control and the pigs fed the diet with deleted Ile that contained 60 and 52% SID Ile:Lys, respectively, and agrees with data reported by Barea et al. (2009b). The results indicate that the Ile:Lys requirement of nursery pigs may not be above 50% in diets without blood products. Mavromichalis et al. (1998) also indicated that supplementation of L-Ile is not required in low-protein, corn–soybean meal–whey–based diets for optimal growth performance for pigs from 8.8 to 18.5 kg BW. The SID Ile:Lys requirement was not reported by Mavromichalis et al. (1998), but the total Ile:Lys requirement was found to be no greater than 60%.

Decreased ADG and ADFI from the pigs fed the diet with deleted L-Trp indicate that feeding 15% SID Trp:Lys was deficient, which is in agreement with the NRC (1998) estimate of 18.5% SID Trp:Lys. Susenbeth (2006) analyzed 33 experiments that evaluated the Trp:Lys requirement in pigs. By adjusting for the intervals of Trp:Lys between dietary treatments, 16% SID Trp:Lys was estimated to be the average minimum requirement of the 33 experiments. Although this value of 16% is below the NRC (1998) recommendation of 18.5%, both of the values confirm the deficiency of 15% that was found in the current study. Research with growing pigs agreed, and the reported requirements ranged from 15.6 to 17.1% SID Trp:Lys and the requirement may vary depending on the level of other essential AA in the diet (Quant et al., 2007, 2009).

The diet without L-Val (57% SID Val:Lys) was deficient for optimal growth, which agrees with data from other experiments (Mavromichalis et al., 2001; Barea et al., 2009a; Gaines et al., 2010). Although some discrepancy exists in evaluating the exact Val requirement of nursery pigs, the data indicate that it is at least 65% of Lys (Wiltafsky et al., 2009; Gaines et al., 2010).

A numerical decrease in performance also occurred for pigs fed the diet without L-Gln and L-Gly compared with the positive control. This may be due to the reduction in dispensable N. One method of measuring dietary dispensable N is by calculating dietary Lys:CP. Ratliff et al. (2004) reported that exceeding 7.00% SID Lys:CP resulted in a decrease in growth performance of nursery pigs from 13 to 26 kg. The calculated value in the diet without L-Gln and L-Gly was of 6.80% SID Lys:CP (7.51% total Lys:CP) and may be approaching the maximum limit. In another study using total Lys, Ratliff et al. (2005b) determined that pigs fed 8.1% total Lys:CP had decreased growth performance compared with those fed 7.1% total Lys:CP. Research with 20- to 50-kg pigs has demonstrated that the combination of Gly and N from an additional AA was required in low-CP, AA-fortified diets for optimal growth (Powell et al., 2009a,b; Southern et al., 2010).

In summary, added L-Trp and L-Val were needed in low-CP, AA-fortified nursery diets to achieve maximum growth performance, whereas the addition of L-Ile was not required. More specifically, SID AA ratios of 15%

Table 8. Evaluation of total Lys:CP on growth performance in nursery pigs (Exp. 3)[1,2]

	Total Lys:CP, %							*P*-value	
Item	6.79	6.92	7.06	7.20	7.35	7.51	SEM	Linear	Quadratic
BW, kg									
d 0	7.22	7.22	7.22	7.27	7.22	7.20	0.07	0.97	0.87
d 14	12.07	12.23	12.23	12.26	12.65	11.91	0.19	0.92	0.46
d 28	19.26	19.40	19.59	19.77	19.83	19.02	0.31	0.99	0.44
d 0 to 14									
ADG, g	347	358	358	356	387	336	12	0.72	0.09
ADFI, g	479	503	498	489	533	495	15	0.20	0.39
G:F	0.726	0.710	0.720	0.727	0.700	0.679	0.012	0.09	0.09
d 14 to 28									
ADG, g	513	512	526	536	513	508	14	0.90	0.19
ADFI, g	821	841	845	846	838	795	19	0.38	0.04
G:F	0.625	0.609	0.620	0.635	0.600	0.639	0.012	0.26	0.42
d 0 to 28									
ADG, g	430	435	442	446	450	422	10	0.91	0.07
ADFI, g	650	672	672	668	686	645	14	0.92	0.07
G:F	0.662	0.647	0.660	0.668	0.700	0.654	0.011	0.99	0.68

[1]A total of 282 nursery pigs (PIC TR4 × 1050; PIC, Hendersonville, TN) were used in a 28-d growth trial to evaluate the effects of total Lys:CP on growth performance. Values represent the means of 7 pens per treatment.

[2]Treatment diets were fed from d 0 to 14 and a common diet fed from d 14 to 28.

Trp:Lys and 57% Val:Lys were not adequate for optimal growth, but 52% Ile:Lys was sufficient. The intermediate performance from pigs fed the diet with L-Gln and L-Gly removed seems to indicate a beneficial effect of Gln or Gly either as a source of dispensable N or as individual AA.

Experiment 3

Analyzed AA levels for experimental diets are shown in Table 3. Differing from the design of the experiment, analyzed AA concentrations varied from the formulated values.

From d 0 to 14, there was a trend toward increased (quadratic, $P = 0.09$) ADG with increasing dietary total Lys:CP up to 7.35%, with a 13% reduction in ADG when the dietary ratio increased from 7.35 to 7.51% (Table 8). Increasing total Lys:CP tended to increase (quadratic, $P = 0.09$) G:F for pigs fed 7.35%, with a 7% decrease in G:F as total Lys:CP increased to 7.51%. From d 14 to 28, there was no difference in ADG or G:F. A response (quadratic, $P = 0.04$) was observed for ADFI, which was the result of an increased ADFI in pigs fed the intermediate diets (7.06 and 7.20% total Lys:CP) during the previous period. Overall (d 0 to 28), there was a trend (quadratic, $P = 0.07$) toward increased ADG and ADFI caused by the highest values in pigs fed a total Lys:CP of 7.35% and the lowest values in pigs fed a total Lys:CP of 7.51%. Dietary treatment did not influence overall G:F.

Limited research has been conducted evaluating the maximum total Lys:CP in pig diets. Lenis et al. (1999) suggested that pigs fed low-protein diets fortified with indispensable AA (**IAA**) have an increased requirement for N from dispensable AA (**DAA**). They speculated this may be due to the N from IAA being used for DAA synthesis if DAA are not adequately supplied in the diet. The NRC (1998) reports that, in pigs, CP in muscle typically contains about 6.5 to 7.5% Lys. The difference in the range of Lys:CP may be due to factors such as BW, sex, genotype, or diet composition (Bikker et al., 1994). Mahan and Shields (1998) agreed with the NRC (1998) estimate, reporting that the carcass composition of a 8.5 kg pig contains 7.3% Lys:CP. Based on the information on the muscle composition, diets with minimum IAA ratios relative to Lys but containing an inadequate amount of protein may result in an inefficient use of AA for protein deposition and growth. However, in the current experiment, growth performance was not different among the pigs fed the different Lys:CP treatment diets.

Experiment 4

Analyzed AA levels for experimental diets are shown in Table 4. Analyzed concentrations were lower than formulated concentrations but are within acceptable limits for analytical variation according to the Association of American Feed Control Officials (2005). With the exception of the diets formulated to be 59.9 and 62.3% SID Val:Lys, which had equal analyzed Val, the AA analysis was in agreement with the design of the experiment, confirming that dietary Val increased as the SID Val:Lys formulations increased.

From d 0 to 14, ADG and ADFI increased (quadratic, $P < 0.01$) as the SID Val:Lys increased from 57.4 to 64.7%, with little changes observed with further increas-

Table 9. Evaluation of standardized ileal digestible (SID) Val:Lys on growth performance in nursery pigs (Exp. 4)[1,2]

	SID Val:Lys, %							*P*-value	
Item	57.4	59.9	62.3	64.7	67.2	69.9	SEM	Linear	Quadratic
BW, kg									
d 0	6.84	6.85	6.85	6.85	6.84	6.84	0.05	0.97	0.93
d 14	9.61	10.18	10.56	10.94	10.97	11.02	0.17	<0.001	0.01
d 28	16.33	16.92	17.43	17.75	17.47	17.80	0.36	0.004	0.19
d 0 to 14									
ADG, g	198	238	266	292	295	298	10	<0.001	0.005
ADFI, g	316	359	418	427	440	434	16	<0.001	0.01
G:F	0.629	0.670	0.636	0.700	0.674	0.690	0.019	0.02	0.82
d 14 to 28									
ADG, g	480	481	491	486	464	485	17	0.82	0.86
ADFI, g	763	783	807	824	784	802	26	0.33	0.27
G:F	0.630	0.610	0.607	0.600	0.592	0.610	0.008	0.01	0.03
d 0 to 28									
ADG, g	339	360	378	389	379	392	12	0.003	0.18
ADFI, g	540	571	613	626	612	618	19	0.002	0.06
G:F	0.629	0.630	0.617	0.600	0.621	0.630	0.009	0.998	0.22

[1]A total of 294 nursery pigs (PIC TR4 × 1050; PIC, Hendersonville, TN) were used in a 28-d growth trial to evaluate the effects of SID Val:Lys on growth performance. Values represent the means of 7 pens per treatment.

[2]Treatment diets were fed from d 0 to 14, and a common diet was fed from d 14 to 28.

es (Table 9). Feed efficiency improved (linear, *P* = 0.02) with increasing Val:Lys, but similar to ADG and ADFI, little improvement was observed in G:F beyond 64.7% of Lys based on the 2-slope breakpoint model. The Val requirement for both optimal ADG and G:F was 65% of Lys. From d 14 to 28, when the common diet was fed, there was no difference in ADG and ADFI; however, G:F became poorer (quadratic, *P* = 0.03) in pigs previously fed increasing Val:Lys. This indicates that a slight compensatory response occurred for G:F. Overall (d 0 to 28), because of the improvement in ADG and ADFI from d 0 to 14, ADG and ADFI increased (linear, *P* = 0.003) as Val:Lys increased. Again, the greatest improvement in ADG and ADFI was observed in pigs fed the diet containing 64.7% Val:Lys during phase 1. There were no differences in G:F for the overall trial.

The predetermined SID Val:Lys of 57.4% used as the lowest dietary treatment is known to be limiting for 7- to 12-kg nursery pigs in Exp. 2 and was confirmed to be deficient in the current experiment. Dietary SID Val:Lys increased up to a maximum level of 69.6%, slightly above the requirement of 68% estimated by the NRC (1998). The minimum SID Val:Lys required for optimal growth in the present study was determined to be 65%. The NRC (1998) and Barea et al. (2009a) suggested SID Val:Lys estimates of 68 and 70%, respectively, but other researchers reported the results similar to the present study (Wiltafsky et al., 2009; Gaines et al., 2010). Wiltafsky et al. (2009) determined the optimum SID Val requirement to be from 66 to 67% of Lys for 8- to 25-kg pigs. Gaines et al. (2010) reported dietary SID Val:Lys of 56 to 80% for pigs ranging from 13 to 32 kg in 3 experiments. Data from these 3 experiments are in agreement with 65% SID Val:Lys for optimal growth observed in the current study.

One possible reason for the variation among SID Val:Lys requirement estimates may be the AA levels or digestibility coefficient estimations of ingredients used in diet formulation. Wiltafsky et al. (2009) used SID AA digestibility coefficients reported by Sauvant et al. (2004), and Barea et al. (2009a) calculated the SID AA using values from the Institut National de la Recherche Agronomique – Association Francaise de Zootechnie tables, which also originated from Sauvant et al. (2004). The SID values from Sauvant et al. (2004) vary slightly from the NRC (1998), which were used in the current trial and Gaines et al. (2010). When the 65% SID Val:Lys diet in the present trial is recalculated using SID AA digestibility coefficients from INRA, the SID Val:Lys ratio is 68%, closer to the estimates of Barea et al. (2009a). The minor differences in SID AA calculations may explain some of the discrepancies among trials. In conclusion, using SID AA coefficients from the NRC (1998), a SID Val:Lys of 65% was sufficient for optimal growth of early nursery pigs.

Experiment 5

Analyzed AA levels for experimental diets are shown in Table 5. Analyzed concentrations were lower than formulated concentrations but are within acceptable limits for analytical variation according to the Association of American Feed Control Officials (2005).

From d 0 to 14 (experimental treatment period), pigs fed high-crystalline AA diets had improved (*P* = 0.04) ADG compared with pigs fed the low-crystalline AA di-

Table 10. Comparison of replacing fish meal, meat and bone meal, and poultry byproduct meal with crystalline AA on growth performance in nursery pigs (Exp. 5)[1,2]

	Crystalline AA level[3,4]								
	Low			High				*P*-value	
Item	Fish meal	Meat and bone meal	Poultry byproduct meal	Fish meal	Meat and bone meal	Poultry byproduct meal	SEM	Protein source	Low AA vs. high AA
BW, kg									
d 0	6.59	6.59	6.59	6.60	6.59	6.59	0.06	0.99	1.00
d 14	10.00	9.74	9.90	10.21	10.04	10.07	0.18	0.58	0.46
d 28	17.28	16.83	17.12	17.45	16.75	17.15	0.33	0.39	0.94
d 0 to 14									
ADG, g	243	224	236	258	247	260	12	0.19	0.04
ADFI, g	366	348	366	381	370	382	14	0.29	0.14
G:F	0.665	0.644	0.645	0.678	0.669	0.681	0.020	0.47	0.14
d 14 to 28									
ADG, g	520	508	515	518	480	515	14	0.09[5]	0.42
ADFI, g	831	827	859	825	801	844	21	0.09[6]	0.38
G:F	0.626	0.614	0.599	0.628	0.599	0.611	0.009	0.03[7]	0.98
d 0 to 28									
ADG, g	381	366	375	388	363	387	11	0.08[8]	0.57
ADFI, g	598	587	612	603	585	611	16	0.13	0.96
G:F	0.638	0.623	0.613	0.644	0.621	0.633	0.010	0.08[9]	0.35

[1]A total of 282 nursery pigs (PIC TR4 × 1050) were used in a 28-d growth trial to evaluate the effects of replacing high amounts of fish meal, meat and bone meal, and poultry byproduct meal with crystalline AA on growth performance of nursery pigs. Values represent the means of 7 pens per treatment.

[2]Treatment diets were fed from d 0 to 14 and a common diet fed from d 14 to 28.

[3]Pigs were fed either a low or a high crystalline AA level.

[4]Pigs were fed either fish meal, meat and bone meal, or poultry byproduct meal.

[5]Effect of fish meal vs. meat and bone meal ($P < 0.10$).

[6]Effect of poultry byproduct meal vs. meat and bone meal ($P < 0.10$).

[7]Effect of fish meal vs. meat and bone meal or poultry byproduct meal ($P < 0.05$).

[8] Effect of fish meal vs. meat and bone meal ($P < 0.10$).

[9] Effect of fish meal vs. poultry byproduct meal ($P < 0.10$).

ets (Table 10). There was no difference in ADG among pigs fed fish meal, meat and bone meal, or poultry byproduct meal. Average daily feed intake and G:F were not different between pigs fed different crystalline AA levels or different protein sources during the first period. From d 14 to 28, when the common diet was fed, there were no differences in ADG or ADFI between pigs fed different crystalline AA levels. There was a tendency ($P = 0.09$) toward decreased ADG for pigs previously fed meat and bone meal and a tendency ($P = 0.09$) for increased ADFI for pigs previously fed poultry byproduct meal. These tendencies resulted in increased ($P = 0.03$) G:F for pigs previously fed fish meal during phase 1 compared with pigs fed diets containing meat and bone meal or poultry byproduct meal. There was no difference between pigs fed different crystalline AA levels during the second period. Overall (d 0 to 28), dietary crystalline AA had no impact on ADG, ADFI, or G:F. Pigs previously fed diets containing fish meal from d 0 to 14 tended ($P = 0.08$) to have increased ADG and G:F for the overall trial compared with pigs fed diets containing meat and bone meal or poultry byproduct meal. There was no difference in ADFI among pigs fed different protein sources. These data indicate that crystalline AA can be used to replace fish meal, meat and bone meal, and poultry byproduct meal in nursery pig diets without negatively influencing growth.

Frantz et al. (2005) also found that fish meal and poultry byproduct meal can be replaced by crystalline AA (L-Lys HCl, L-Thr, DL-Met, L-Val, L-Ile, and L-Trp). Other experiments also indicated that fish meal can be replaced in nursery diets by crystalline AA with no negative effects on growth performance (Ratliff et al., 2005a; Bradley et al., 2008). Some studies have, however, indicated that animal protein sources cannot be replaced with crystalline AA and maintain equal performance. These studies with negative responses to low-CP, AA-fortified diets may be due to formulating diets on a total vs. SID AA basis. Other possible explanations may include limitations of fourth and fifth limiting AA, variations in lactose levels, or inadequate dispensable N concentrations (Kats et al., 1994; Davis et al., 1997; Chung et al., 1999). In conclusion, these results indicate that crystalline AA in nursery pigs diets can replace fish meal, meat and bone meal, and poultry byproduct meal when balanced for minimum SID AA ratios with no negative effect on growth performance.

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