Bioavailability of L-lysine sulfate relative to L-lysine HCl for growing–finishing pigs

Qingyun Li,[†] Stacie A. Gould,[†] John Khun Kyaw Htoo,[‡] J. Caroline González-Vega,[‡] and John F. Patience[†,1]

[†]Department of Animal Science, Iowa State University, Ames, IA 50011; and [‡]Evonik Nutrition and Care GmbH, 63457 Hanau-Wolfgang, Germany

ABSTRACT: The objective of this study was to evaluate the relative bioavailability (RBV) of L-Lys sulfate in comparison to L-Lys HCl based on the growth performance response from approximately 26 to 48 kg and from approximately 68 to 114 kg. The effect of Lys source on blood urea nitrogen (BUN), digestibility of dry matter (DM) and sulfur (S), as well as carcass characteristics was determined. A total of 280 growing pigs (25.9 ± 0.25 kg BW) were randomly assigned to one of seven dietary treatments in 56 pens, with five pigs per pen. The diets included a Lys-deficient basal diet (65% of requirement) and the basal diet supplemented with three graded levels of Lys (75%, 85%, and 95% of requirement), as either L-Lys HCl (78.8% Lys purity) or L-Lys sulfate (54.6% Lys purity). The experiment lasted for 112 d, with four dietary phases: Phase 1 lasted for 4 wk (BW: 25.9 to 47.5 kg), Phase 2 lasted for 3 wk (common commercial diet as washout period), Phase 3 lasted for 5 wk (BW: 67.5 to 98.2 kg), and Phase 4 lasted for 3 or 4 wk to reach an average market weight of 114.2 kg. Fresh fecal samples of pigs fed the highest levels of Lys (both Lys sources) were collected on 7 to 10 days after the beginning of Phase 3 for digestibility assay. Blood samples were collected on day 21 and day 81 to determine BUN. Carcass data were collected at a commercial packing plant. Data were analyzed using PROC GLM of SAS (9.4) according to a completely randomized design with pen as the experimental unit. The RBV of L-Lys sulfate was determined using the multiple regression slope-ratio method. Increasing levels of Lys, independent of source, increased ($P < 0.05$) BW, ADG, and feed efficiency during Phases 1, 3, and 4; market BW increased linearly ($P < 0.01$) and backfat and BUN decreased linearly ($P < 0.01$). Lysine source had no impact on growth performance, carcass characteristics, BUN, or digestibility of S and DM. The RBV of L-Lys sulfate compared with L-Lys HCl was also not different based upon ADG or G:F during Phase 1, 3, or 4. These data suggest that the bioavailability of Lys in L-Lys sulfate and L-Lys HCl is at least equivalent for growing–finishing pigs.

Key Words: bioavailability, carcass, growing–finishing pigs, L-Lys HCl, L-Lys sulfate

Transl. Anim. Sci. 2019.3:1254–1262
doi: 10.1093/tas/txz094

INTRODUCTION

Lysine is typically the first-limiting AA in swine diets based on grains and soybean meal. Crystalline Lys is one tool available to nutritionists to meet the pig's Lys requirement for lean muscle growth. There is a growing desire to reduce the crude protein (CP) content of diets in order to reduce the quantity of nitrogen excreted by the pig in the urine and feces, and thus reduce the quantity of land on which manure needs to be spread (Jones et al., 2014). There is also an

[1]Corresponding author: jfp@iastate.edu
Received April 18, 2019.
Accepted June 19, 2019.

interest to reduce dietary CP in the diets of young pigs to reduce the risk of gastrointestinal distress and thus diarrhea, especially in situations where antibiotics cannot be used in the feed or water (Heo et al., 2009). In these instances, supplemental Lys is an effective way for the nutritionist to meet the pig's requirement at the lowest possible protein level.

Currently, most of the supplemental Lys used in pig diets is in the form of L-Lys HCl (78.8% Lys); more recently, an alternative source of supplemental Lys from L-Lys sulfate (≥ 54.6% Lys) has been developed and evaluated for bioavailability relative to L-Lys HCl. The relative bioavailability (RBV) of L-Lys sulfate is not different from the RBV of L-Lys HCl (assuming 100% bioavailable) for starter (10 to 15 kg) and growing (57 to 87 kg) pigs (Smiricky-Tjardes et al., 2004; Htoo et al., 2016). However, there is limited information about the RBV of these two sources of Lys for pigs with a BW between 25 and 55 kg and greater than 90 kg. Therefore, the objective of this experiment was to evaluate the RBV of L-Lys sulfate in comparison to L-Lys HCl based on growth performance responses for pigs in the early grower and late finisher stages of production. Additionally, the effect of Lys source on carcass characteristics of finishing pigs was evaluated.

MATERIALS AND METHODS

All procedures used in this experiment adhered to guidelines for the ethical and humane use of animals for research and were approved by the Iowa State University Institutional Animal Care and Use Committee (#3-17-8458-S).

Animals, Experimental Design, and Dietary Treatments

The experiment was conducted at the Swine Nutrition Farm at Iowa State University. A total of 280 growing pigs (25.9 ± 0.25 kg initial BW; 140 barrows and 140 gilts; L337 × Camborough, PIC, Hendersonville, TN) were randomly assigned to one of seven dietary treatments in 56 pens, with eight pens per treatment and five pigs per pen. The average pig initial BW was balanced among treatments. Barrows and gilts were separately housed and balanced among treatments. The experiment lasted for 112 days. All animals were fed ad libitum and had free access to water from nipple drinkers within each pen.

There were 4 dietary phases: Phase 1 lasted for 4 wk (BW: 25.9 to 47.5 kg), Phase 2 lasted for 3 wk (washout period), Phase 3 lasted for 5 wk (BW: 67.5 to 98.2 kg), and Phase 4 lasted for 3 or 4 wk to reach an average market weight of 114.2 kg. Pigs were kept on the same treatment regime during Phases 3 and 4 as they received in Phase 1. All pigs were fed a common late grower commercial diet purchased from Key Cooperative (Nevada, IA) during Phase 2. Half of the heaviest pens were marketed on day 105 (first cut) and the other half were marketed on day 112 (second cut). Thus, marketing was done on a similar weight rather than time basis.

For Phases 1, 3, and 4, seven diets were formulated based on corn and soybean meal, consisting of a Lys-deficient basal diet and the basal diet supplemented with one of three graded levels (0.10%, 0.20%, and 0.30% for Phase 1; 0.07%, 0.14%, and 0.21% for Phase 3; 0.05%, 0.10%, and 0.15% for Phase 4) of Lys either as L-Lys HCl (78.8% purity) or L-Lys sulfate (54.6% purity; Evonik Nutrition & Care GmbH, Germany) on an equivalent Lys basis. Lysine supplemental levels of 0.10%, 0.20%, and 0.30% were used throughout the manuscript to indicate the 3 increasing Lys supplemental levels. Both Lys sources were added at the expense of corn starch in the basal diet to keep the diet composition the same across all treatments as much as possible. The diets were formulated on the basis of analyzed AA contents and the SID coefficients of AA (AminoDat 5.0; Evonik Nutrition & Care GmbH, Germany) to meet or exceed AA requirements except for Lys (NRC, 2012).

The Lys-deficient basal diet was formulated to provide approximately 65% of the SID Lys requirement, based on NRC (2012) for the Phase 1 diet, and Elsbernd et al. (2017) for the Phase 3 and 4 diets. The latter defined the Lys requirement in the same barn using the same genetics and at the same BW. The treatment diets supplied approximately 75%, 85%, and 95% of the SID Lys requirement by supplementing Lys from either L-Lys HCl or L-Lys sulfate. The total AA and other nutrient concentration as well as analyzed total AA and CP for each phase diet are shown in Tables 1–3.

Data Collection

Pigs were individually weighed on the first and last day of each phase as well as before market. Feed intake was recorded for the same periods starting with day 0, to allow for calculation of ADG, ADFI, and G:F. Because pigs were fed a common diet during Phase 2, feed intake was

Table 1. Ingredient composition and nutrient concentration of Phase 1 diets (day 0 to 28; as-fed basis)

		L-Lys HCl (Lys-equivalence), %			L-Lys sulfate (Lys-equivalence), %		
Item	Basal	0.10	0.20	0.30	0.10	0.20	0.30
Ingredients, %							
Corn	75.23	75.23	75.23	75.23	75.23	75.23	75.23
Soybean meal	19.28	19.28	19.28	19.28	19.28	19.28	19.28
Corn gluten meal	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Monocalcium phosphate	1.07	1.07	1.07	1.07	1.07	1.07	1.07
Limestone	1.03	1.03	1.03	1.03	1.03	1.03	1.03
Salt	0.22	0.22	0.22	0.22	0.22	0.22	0.22
Vitamin premix[1]	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Mineral premix[2]	0.20	0.20	0.20	0.20	0.20	0.20	0.20
DL-Methionine	0.12	0.12	0.12	0.12	0.12	0.12	0.12
L-Threonine	0.12	0.12	0.12	0.12	0.12	0.12	0.12
L-Tryptophan	0.04	0.04	0.04	0.04	0.04	0.04	0.04
L-Lys HCl (78.8%)	—	0.13	0.25	0.38	—	—	—
L-Lys sulfate (54.6%)	—	—	—	—	0.18	0.37	0.55
Corn starch	0.55	0.42	0.30	0.17	0.37	0.18	0.00
Analyzed DM, %	87.25	86.87	86.40	87.24	87.04	87.34	87.15
Calculated energy and nutrient levels[3]							
Net energy, Mcal/kg	2.52	2.52	2.52	2.52	2.52	2.52	2.52
Crude protein, %	15.79 (14.82)	15.91 (14.63)	16.03 (14.66)	16.15 (14.65)	15.94 (14.66)	16.08 (14.58)	16.23 (14.92)
Total Ca, %	0.66	0.66	0.66	0.66	0.66	0.66	0.66
STTD P, %	0.31	0.31	0.31	0.31	0.31	0.31	0.31
Total Lys, %	0.74	0.84	0.94	1.04	0.84	0.94	1.04
SID Lys, %	0.64 (0.76)	0.74 (0.84)	0.84 (0.92)	0.94 (1.03)	0.74 (0.86)	0.84 (0.95)	0.94 (1.09)
SID Met + Cys, %	0.58 (0.63)	0.58 (0.62)	0.58 (0.63)	0.58 (0.62)	0.58 (0.63)	0.58 (0.61)	0.58 (0.63)
SID Thr, %	0.61 (0.68)	0.61 (0.68)	0.61 (0.70)	0.61 (0.69)	0.61 (0.68)	0.61 (0.66)	0.61 (0.71)
SID Trp, %	0.19 (0.21)	0.19 (0.20)	0.19 (0.21)	0.19 (0.21)	0.19 (0.21)	0.19 (0.21)	0.19 (0.21)
SID Val, %	0.65 (0.72)	0.65 (0.72)	0.65 (0.71)	0.65 (0.71)	0.65 (0.73)	0.65 (0.72)	0.65 (0.71)
SID Leu, %	1.37 (1.48)	1.37 (1.48)	1.37 (1.47)	1.37 (1.42)	1.37 (1.47)	1.37 (1.45)	1.37 (1.44)
SID Ile, %	0.56 (0.63)	0.56 (0.63)	0.56 (0.62)	0.56 (0.62)	0.56 (0.63)	0.56 (0.62)	0.56 (0.62)

[1]Provided per kg of diet: 4,288 IU vitamin A, 490 IU vitamin D, 35 IU vitamin E, 2 mg vitamin K, 8 mg riboflavin, 39 mg niacin, 19 mg pantothenic acid, and 0.04 mg vitamin B_{12}.

[2]Provided per kg of diet: 220 mg Fe (iron sulfate), 220 mg Zn (zinc sulfate), 52 mg Mn (manganese sulfate), 22 mg Cu (copper sulfate), 0.4 mg I (calcium iodate), and 0.4 mg Se (sodium selenite).

[3]Values in parenthesis are analyzed crude protein and total AA concentrations.

STTD = standardized total tract digestible; SID = standardized ileal digestible.

not recorded and performance was not reported. For carcass evaluation, all pigs were slaughtered at a commercial packing plant (Tyson Foods, Perry, IA). After slaughter, internal organs were removed to measure hot carcass weight (HCW). Carcass backfat and loin depth were measured using a fat-o-meter probe between the third and fourth last ribs, 7 cm off the midline. Percent lean was calculated using a proprietary equation (Tyson Feeds, Perry, IA).

Blood samples were collected by venipuncture from the same 2 pigs within each pen on day 21 and day 81 to determine blood urea nitrogen (BUN) concentration. Fresh fecal samples were collected from all pens receiving the diets containing the highest Lys supplemental level, approximately 7 to 10 days after the beginning of Phase 3.

Analytical Methods

Feces were thawed and homogenized, and then dried at 55 °C to a constant weight. Diet and fecal samples were ground to 1 mm and analyzed for dry matter (DM; method 930.15; AOAC, 2007). Sulfur content was analyzed through inductively coupled plasma optical emission spectrometry (Optima 7000 DV, PerkinElmer, Waltham, MA; Pogge et al., 2014). Titanium dioxide (TiO_2) was analyzed using a spectrophotometer (Synergy 4; BioTek, Winooski,

Table 2. Ingredient composition and nutrient concentration of Phase 3 diets (day 49 to 84; as-fed basis)

		L-Lys HCl (Lys-equivalence), %			L-Lys sulfate (Lys-equivalence), %		
Item	Basal	0.07	0.14	0.21	0.07	0.14	0.21
Ingredients, %							
Corn	85.19	85.19	85.19	85.19	85.19	85.19	85.19
Soybean meal	9.80	9.80	9.80	9.80	9.80	9.80	9.80
Monocalcium phosphate	0.81	0.81	0.81	0.81	0.81	0.81	0.81
Limestone	0.82	0.82	0.82	0.82	0.82	0.82	0.82
Salt	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Vitamin premix[1]	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Mineral premix[2]	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Soybean oil	0.36	0.36	0.36	0.36	0.36	0.36	0.36
DL-Methionine	0.06	0.06	0.06	0.06	0.06	0.06	0.06
L-Threonine	0.10	0.10	0.10	0.10	0.10	0.10	0.10
L-Tryptophan	0.02	0.02	0.02	0.02	0.02	0.02	0.02
L-Lys HCl (78.8%)	—	0.09	0.18	0.27	—	—	—
L-Lys sulfate (54.6%)	—	—	—	—	0.13	0.26	0.38
Corn starch	2.00	1.91	1.82	1.73	1.87	1.74	1.62
Analyzed DM, %	86.74	86.72	86.87	86.77	86.67	86.80	86.83
Calculated energy and nutrient levels[3]							
Net energy, Mcal/kg	2.59	2.59	2.59	2.59	2.59	2.59	2.59
Crude protein, %	10.73 (10.08)	10.81 (10.23)	10.90 (10.35)	10.98 (10.76)	10.83 (10.65)	10.94 (—)	11.04 (10.22)
Total Ca, %	0.52	0.52	0.52	0.52	0.52	0.52	0.52
STTD P, %	0.24	0.24	0.24	0.24	0.24	0.24	0.24
Total Lys, %	0.47	0.54	0.61	0.68	0.54	0.61	0.68
SID Lys, %	0.39 (0.48)	0.46 (0.54)	0.53 (0.61)	0.60 (0.70)	0.46 (0.58)	0.53 (0.64)	0.60 (0.68)
SID Met + Cys, %	0.39 (0.45)	0.39 (0.43)	0.39 (0.45)	0.39 (0.43)	0.39 (0.46)	0.39 (0.41)	0.39 (0.42)
SID Thr, %	0.43 (0.48)	0.43 (0.47)	0.43 (0.46)	0.43 (0.47)	0.43 (0.49)	0.43 (0.47)	0.43 (0.52)
SID Trp, %	0.11 (0.13)	0.11 (0.13)	0.11 (0.13)	0.11 (0.13)	0.11 (0.13)	0.11 (0.12)	0.11 (0.12)
SID Val, %	0.44 (0.48)	0.44 (0.49)	0.44 (0.48)	0.44 (0.51)	0.44 (0.51)	0.44 (0.47)	0.44 (0.49)
SID Leu, %	0.96 (0.97)	0.96 (0.98)	0.96 (1.00)	0.96 (1.04)	0.96 (1.02)	0.96 (0.95)	0.96 (0.98)
SID Ile, %	0.36 (0.39)	0.36 (0.41)	0.36 (0.40)	0.36 (0.42)	0.36 (0.42)	0.36 (0.39)	0.36 (0.40)

[1]Provided per kg of diet: 4,288 IU vitamin A, 490 IU vitamin D, 35 IU vitamin E, 2 mg vitamin K, 8 mg riboflavin, 39 mg niacin, 19 mg pantothenic acid, and 0.04 mg vitamin B_{12}.

[2]Provided per kg of diet: 220 mg Fe (iron sulfate), 220 mg Zn (zinc sulfate), 52 mg Mn (manganese sulfate), 22 mg Cu (copper sulfate), 0.4 mg I (calcium iodate), and 0.4 mg Se (sodium selenite).

[3]Values in parenthesis are analyzed crude protein and total AA concentrations.

STTD = standardized total tract digestible; SID = standardized ileal digestible.

VT) according to the method of Leone (1973). Diets were also analyzed for nitrogen (N; method 990.03; AOAC, 2007; TruMac; LECO Corp., St. Joseph, MI); EDTA (9.56% N; Leco Corporation) was used as a standard for calibration and was determined to contain 9.56 ± 0.02% of N. Crude protein was calculated as N × 6.25. Total AA analyses of diets were determined by ion-exchange chromatography with post-column derivatization with ninhydrin. Amino acids were oxidized with performic acid, which was neutralized with Na metabisulfite (Llames and Fontaine, 1994; Commission Directive, 1998). Amino acids were liberated from the protein by hydrolysis with 6 *N* HCl for 24 h at 110 °C and quantified with the internal standard by measuring the absorption of reaction products with ninhydrin at 570 nm. Tryptophan was determined by high-performance liquid chromatography with fluorescence detection (extinction 280 nm, emission 356 nm), after alkaline hydrolysis with barium hydroxide octahydrate for 20 h at 110 °C (Commission Directive, 2000). The BUN assay was completed at the ISU Veterinary Diagnostic Lab using the VITROS BUN/UREA Slide method on VIREOS5.1 FS chemistry system (Orthi Clinical Diagnostics, Raritan, NJ). All chemical analyses were performed in duplicate.

Statistical Analysis

Data were analyzed using PROC GLM of SAS (9.4; SAS Inst. Inc., Cary, NC) according to a

Table 3. Ingredient composition and nutrient concentration of Phase 4 diets (day 84 to 105, as-fed basis)

		L-Lys HCl (Lys-equivalence), %			L-Lys sulfate (Lys-equivalence), %		
Item	Basal	0.05	0.10	0.15	0.05	0.10	0.15
Ingredients, %							
Corn	90.80	90.80	90.80	90.80	90.80	90.80	90.80
Soybean meal	6.20	6.20	6.20	6.20	6.20	6.20	6.20
Monocalcium phosphate	0.68	0.68	0.68	0.68	0.68	0.68	0.68
Limestone	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Salt	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Vitamin premix[1]	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Mineral premix[2]	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Soybean oil	0.41	0.41	0.41	0.41	0.41	0.41	0.41
DL-Methionine	—	—	—	—	—	—	—
L-Threonine	0.04	0.04	0.04	0.04	0.04	0.04	0.04
L-Tryptophan	0.01	0.01	0.01	0.01	0.01	0.01	0.01
L-Lys HCl (78.8%)	—	0.06	0.13	0.19	—	—	—
L-Lys sulfate (54.6%)	—	—	—	—	0.09	0.18	0.27
Corn starch	0.27	0.21	0.14	0.08	0.18	0.09	0.00
Analyzed DM, %	86.56	86.65	86.45	86.61	86.4	86.24	87.59
Calculated energy and nutrient levels[3]							
Net energy, Mcal/kg	2.61	2.61	2.61	2.61	2.61	2.61	2.61
Crude protein, %	9.34 (9.43)	9.40 (8.79)	9.46 (8.91)	9.52 (8.58)	9.41 (8.63)	9.48 (9.39)	9.56 (9.70)
Total Ca, %	0.46	0.46	0.46	0.46	0.46	0.46	0.46
STTD P, %	0.21	0.21	0.21	0.21	0.21	0.21	0.21
Total Lys, %	0.38	0.43	0.48	0.53	0.43	0.48	0.53
SID Lys, %	0.31 (0.42)	0.36 (0.43)	0.41 (0.47)	0.46 (0.53)	0.36 (0.42)	0.41 (0.50)	0.46 (0.51)
SID Met + Cys, %	0.31 (0.35)	0.31 (0.34)	0.31 (0.33)	0.31 (0.34)	0.31 (0.33)	0.31 (0.35)	0.31 (0.33)
SID Thr, %	0.32 (0.39)	0.32 (0.36)	0.32 (0.35)	0.32 (0.36)	0.32 (0.35)	0.32 (0.39)	0.32 (0.38)
SID Trp, %	0.08 (0.10)	0.08 (0.09)	0.08 (0.09)	0.08 (0.10)	0.08 (0.09)	0.08 (0.10)	0.08 (0.10)
SID Val, %	0.38 (0.46)	0.38 (0.43)	0.38 (0.42)	0.38 (0.44)	0.38 (0.42)	0.38 (0.45)	0.38 (0.42)
SID Leu, %	0.89 (0.95)	0.89 (0.91)	0.89 (0.89)	0.89 (0.91)	0.89 (0.90)	0.89 (0.95)	0.89 (0.90)
SID Ile, %	0.30 (0.37)	0.30 (0.35)	0.30 (0.34)	0.30 (0.35)	0.30 (0.34)	0.30 (0.36)	0.30 (0.33)

[1]Provided per kg of diet: 4,288 IU vitamin A, 490 IU vitamin D, 35 IU vitamin E, 2 mg vitamin K, 8 mg riboflavin, 39 mg niacin, 19 mg pantothenic acid, and 0.04 mg vitamin B_{12}.

[2]Provided per kg of diet: 220 mg Fe (iron sulfate), 220 mg Zn (zinc sulfate), 52 mg Mn (manganese sulfate), 22 mg Cu (copper sulfate), 0.4 mg I (calcium iodate), and 0.4 mg Se (sodium selenite).

[3]Values in parenthesis are analyzed crude protein and total AA concentrations.

STTD = standardized total tract digestible; SID = standardized ileal digestible.

completely randomized design with pen as the experimental unit. The interaction effect between Lys levels and sources was evaluated according to a 2 × 3 factorial design by removing the basal diet treatment. The model included Lys level, Lys source, sex, and their interactions. There were no Lys level × Lys source × sex and Lys level × source interactions for any response variable. Therefore, the final model included treatment (Lys-deficient basal diet and 6 Lys-supplemented diets), sex, and their interaction. Orthogonal–polynomial contrasts were performed to determine linear and quadratic effects of Lys level and the effect of Lys source on response variables. No quadratic effects of Lys level were detected for any response variables; thus only linear effects of Lys level were reported. Initial BW was used as a covariate for growth performance and market weight was used as a covariate for carcass composition. Two pigs from 2 different pens fed 0.2% L-Lys sulfate-supplemented diet were removed from the Phase 4 performance data analysis due to significant weight losses (>8 kg). The two-sample *t*-test was used to analyze the digestibility data.

To estimate the RBV of L-Lys sulfate relative to L-Lys HCl, ADG and G:F data were fitted in a multivariate linear regression model using the following equation:

$$Y = b_0 + b_1x_1 + b_2x_2$$

where Y is the response variable, b_0 is the common y-intercept of the two lines, b_1 is the slope for response to L-Lys HCl in the diet, x_1 is the percent

Table 4. Effect of lysine sources and levels on growth performance of growing–finishing pigs[1]

		L-Lys HCl, %			L-Lys sulfate, %				*P*-value[2]	
Item	Basal	0.10	0.20	0.30	0.10	0.20	0.30	SEM	Source	Linear
No. pens	8	8	8	8	8	8	8			
Phase 1 (day 0 to 28)										
Initial BW, kg	25.7	26.1	25.8	25.8	26.0	26.2	25.9	0.7	0.761	0.885
Final BW, kg	45.4	46.4	48.4	48.1	47.1	48.8	48.4	0.5	0.624	<0.01
ADG, kg	0.70	0.73	0.81	0.80	0.75	0.81	0.80	0.02	0.690	<0.01
ADFI, kg	1.68	1.71	1.75	1.68	1.76	1.77	1.69	0.03	0.480	0.901
G:F	0.42	0.43	0.46	0.48	0.43	0.46	0.48	0.01	0.773	<0.01
Phase 3 (day 49 to 84)										
Initial BW, kg	66.7	66.2	68.3	67.6	67.1	69.0	67.7	1.0	0.715	0.271
Final BW, kg	92.7	94.2	99.9	101.3	97.3	101.4	100.6	1.7	0.476	<0.01
ADG, kg	0.74	0.78	0.90	0.96	0.87	0.93	0.94	0.03	0.307	<0.01
ADFI, kg	2.73	2.63	2.87	2.83	2.85	2.85	2.79	0.08	0.484	0.277
G:F	0.27	0.30	0.32	0.34	0.30	0.33	0.34	0.01	0.425	<0.01
Phase 4 (day 84 to 105)										
Initial BW, kg	92.7	94.2	99.9	101.3	97.3	101.4	100.6	1.7	0.476	<0.01
Final BW, kg	105.7	106.9	115.0	116.3	111.5	116.4	115.8	2.0	0.342	<0.01
ADG, kg	0.62	0.60	0.72	0.71	0.69	0.70	0.72	0.04	0.315	0.014
ADFI, kg	2.94	2.75	2.89	2.92	3.03	2.96	2.90	0.09	0.049	0.966
G:F	0.21	0.22	0.25	0.24	0.23	0.23	0.25	0.01	0.905	0.002
Phases 3 to 4 (day 49 to 105)										
Initial BW, kg	66.7	66.2	68.3	67.6	67.1	69.0	67.7	1.0	0.715	0.271
Final BW, kg	105.7	106.9	115.0	116.3	111.5	116.4	115.8	2.0	0.342	<0.01
ADG, kg	0.70	0.71	0.83	0.87	0.80	0.85	0.86	0.03	0.149	<0.01
ADFI, kg	2.81	2.67	2.88	2.86	2.92	2.90	2.83	0.07	0.166	0.467
G:F	0.25	0.27	0.29	0.30	0.27	0.29	0.30	0.00	0.607	<0.01

[1]Diets included a Lys-deficient basal diet and the basal diet supplemented with one of three graded levels (0.10%, 0.20%, and 0.30% for Phase 1; 0.07%, 0.14%, and 0.21% for Phase 3; 0.05%, 0.10%, and 0.15% for Phase 4) of Lys, either as L-Lys HCl (78.8% purity) or L-Lys sulfate (54.6% purity) on an equivalent Lys basis.

[2]*P*-value of orthogonal contrasts: sources = *P* value between L-Lys HCl and L-Lys sulfate diets; linear = linear effects of graded levels of Lys (combined two Lys sources because there was no source by level interaction effect).

supplemental L-Lys HCl in the diet, b_2 is the slope for response to L-Lys sulfate in the diet, and x_2 is the percent supplemental L-Lys sulfate in the diet (Littell et al., 1997). The bioavailability of L-Lys sulfate relative to L-Lys HCl was calculated by the slope-ratio technique ($b_2/b_1 \times 100$). An ESTIMATED statement in PROC NLMIXED was performed to obtain 95% confidence interval of the RBV and determine the statistical significance between b_1 and b_2. Results were considered significant if $P < 0.05$ and tendencies if $0.05 \leq P < 0.10$.

RESULTS AND DISCUSSION

Pig Removals and Health Status

Nine pigs died during the study and were not related to dietary treatments. Dead pigs were necropsied and tested to be positive for *Actinobacillus suis* and *Pasteurella* infections. Pigs suffered from an influenza outbreak during Phase 2. Because the experiment was conducted in summer, pigs also experienced heat stress.

Growth and Carcass Performance and BUN

There were no differences in growth performance between L-Lys HCl and L-Lys sulfate (Table 4), which agrees with results by Smiricky-Tjardes et al. (2004) and Htoo et al. (2016). With increasing levels of Lys supplementation from either L-Lys HCl or L-Lys sulfate, pig market BW, ADG and G:F during Phases 1, 3, 4, and 3 to 4 increased linearly ($P < 0.05$). In agreement with the current results, Htoo et al. (2016) also reported that supplemental Lys from L-Lys HCl or L-Lys sulfate linearly increased the overall ADG and G:F in growing pigs (57 to 87 kg) when fed a Lys-deficient diet.

Table 5. Effect of lysine sources and levels on carcass performance and BUN of pigs[1]

		L-Lys HCl, %			L-Lys sulfate, %				*P*-value[2]	
Item	Basal	0.10	0.20	0.30	0.10	0.20	0.30	SEM	Source	Linear
HCW, kg	82.2	80.0	86.1	86.8	84.7	87.5	87.4	0.9	0.289	0.237
Dressing percentage, %	74.38	73.77	74.49	73.70	74.78	74.66	74.84	0.70	0.260	0.213
Backfat, mm	14.14	12.89	13.10	11.91	13.70	13.44	12.91	0.51	0.143	<0.01
Loin depth, mm	59.64	59.79	63.18	63.85	62.73	63.21	63.96	1.45	0.524	0.248
Lean, %	54.68	55.09	55.64	54.91	55.40	54.14	54.68	1.22	0.607	0.865
BUN, mg/dL										
Day 21	11.1	8.4	6.8	6.0	8.5	6.7	5.8	0.5	0.852	<0.01
Day 81	10.3	8.7	6.5	4.6	7.6	6.5	5.9	0.5	0.826	<0.01

[1]*n* = 8 pens per treatment; diets included a Lys-deficient basal diet and the basal diet supplemented with one of three graded levels (0.10%, 0.20%, and 0.30% for Phase 1; 0.07%, 0.14%, and 0.21% for Phase 3; 0.05%, 0.10%, and 0.15% for Phase 4) of Lys, either as L-Lys HCl (78.8% purity) or L-Lys sulfate (54.6% purity) on an equivalent Lys basis.

[2]*P*-value of orthogonal contrasts: sources = *P* value between L-Lys HCl and L-Lys sulfate diets; linear = linear effects of graded levels of Lys (combined two Lys sources because there was no source by level interaction effect).

Table 6. Effect of lysine sources on apparent total tract digestibility of dry matter and sulfur in pigs receiving diets containing the highest Lys supplemental level during Phase 3[1]

Item	L-Lys HCl, 0.30%	L-Lys sulfate, 0.30%	SEM	*P*-value
Dry matter	85.66	85.18	0.64	0.471
Sulfur	74.19	71.79	1.93	0.234

[1]*n* = 8 pens per treatment; fresh fecal samples were collected from all pens receiving the diets containing the highest Lys supplemental level, approximately 7 to 10 d after the beginning of Phase 3 (day 91 to 94).

For carcass characteristics, backfat thickness decreased ($P < 0.01$) with increasing levels of Lys supplied by either L-Lys HCl or L-Lys sulfate (Table 5). There was no difference in backfat thickness between the two Lys sources. Neither Lys source nor level affected HCW, dressing percentage, loin depth, or estimated lean percentage. In agreement with findings in this study, it was reported that backfat depth of pigs decreased with increasing Lys levels (Goodband et al., 1990; Witte et al., 2000) and increasing Lys:ME ratio (Grandhi and Cliplef, 1997; Apple et al., 2004).

The 2 sources of Lys did not differ in BUN on day 21 or day 81 (Table 5). However, increasing Lys supplementation levels linearly decreased BUN on both collection days ($P < 0.01$). The concentration of BUN is frequently used as a response criterion to determine the requirement for Lys and other AA in pigs (Coma et al., 1995; Knowles et al., 1997). Decreased BUN concentration is normally associated with improved nitrogen retention and utilization in pigs (Kohn et al., 2005). Because diets were below the Lys requirement, a linear reduction in BUN was observed with increasing dietary Lys levels, suggesting a more efficient use of dietary AA for protein deposition. This agrees with the linear improvement in ADG and G:F observed in this study with increasing levels of Lys supplementation.

Apparent Total Tract Digestibility of Sulfur and Dry Matter

The analyzed S content of the diet containing 0.3% added L-Lys HCl or 0.3% added L-Lys sulfate was 0.085% and 0.084%, respectively. No differences were detected in the apparent total tract digestibility (ATTD) of DM and S, between the two highest Lys treatments (Table 6). These results appear to support the similar growth performance between the two Lys sources observed in this study.

Relative Bioavailability

The RBV of L-Lys sulfate compared with L-Lys HCl was not different based on growth performance of Phases 1, 3, and 4 (Fig. 1A to F). In agreement with current results, Palencia et al. (2019) and Htoo et al. (2016) reported equivalent bioavailability between these two Lys sources using ADG and G:F as response criteria in nursery pigs (6 to 21 kg) and growing pigs (57 to 87 kg), respectively. The lack of difference in RBV between L-Lys sulfate and L-Lys HCl also agreed with the lack of differences in ADG, G:F, and digestibility

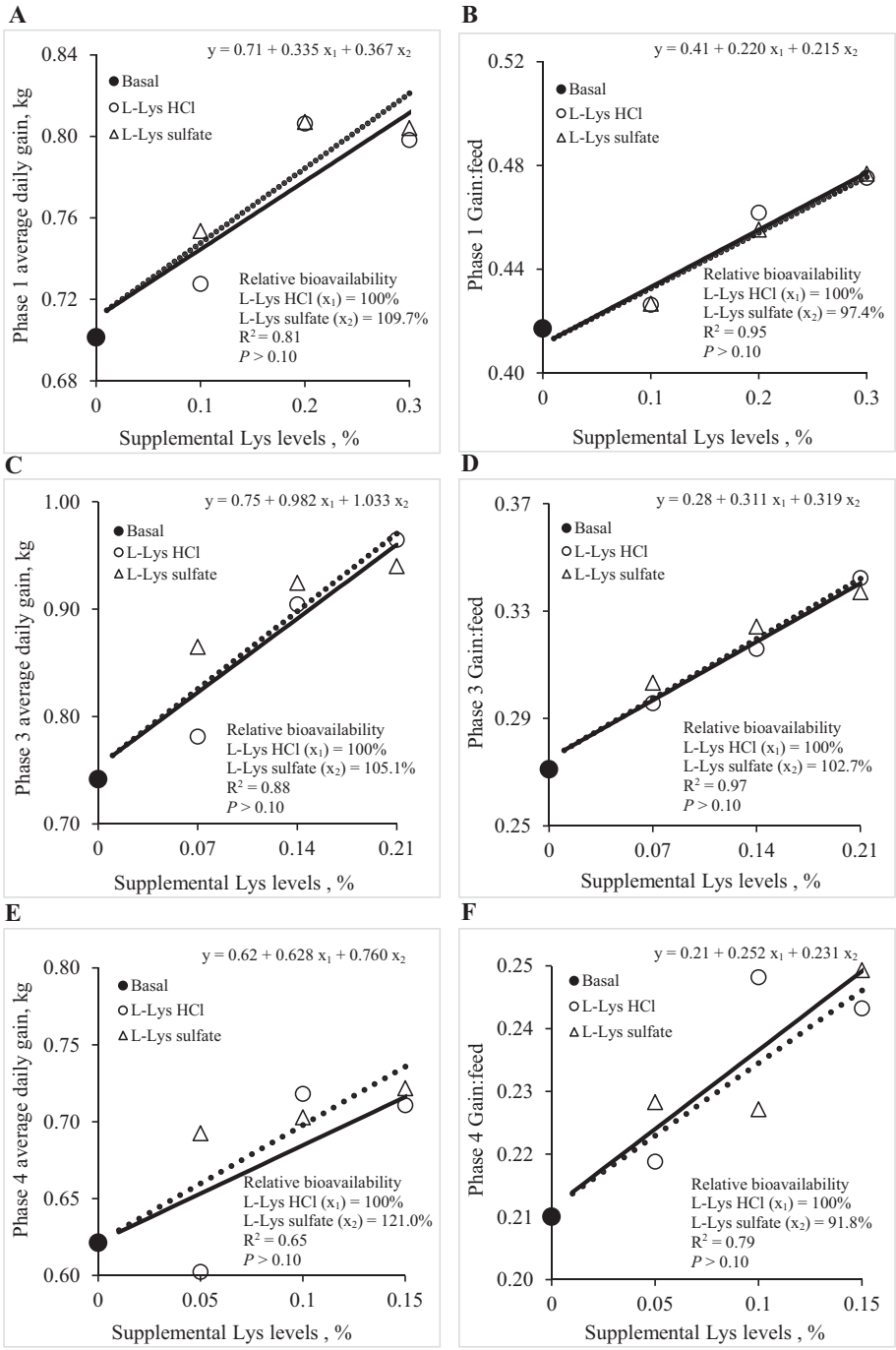

Figure 1. Relative bioavailability (RBV) of L-Lys sulfate compared to L-Lys HCl based on Phase 1 ADG (A), Phase 1 G:F (B), Phase 3 ADG (C), Phase 3 G:F (D), Phase 4 ADG (E), and Phase 4 G:F (F) as a response of supplemental Lys level in growing–finishing pigs (26 to 114 kg). $P > 0.10$ indicates the RBV was not different. The 95% confidence interval of the RBV for Phase 1 ADG, Phase 1 G:F, Phase 3 ADG, Phase 3 G:F, Phase 4 ADG, and Phase 4 G:F were 59.9% to 159.4%, 77.8% to 117.0%, 68.9% to 141.4%, 86.3% to 119.2%, 35.4% to 206.7%, and 47.6% to 136.1%, respectively.

of DM and S between the two Lys sources observed in this study.

In conclusion, supplementing Lys, irrespective of source, to a Lys-deficient basal diet linearly improved growth performance and decreased backfat of growing–finishing pigs. The RBV of L-Lys sulfate is equivalent to that of L-Lys HCl based on growth performance for growing–finishing pigs. Additionally, L-Lys sulfate performed similarly as L-Lys HCl in DM and S digestibility and BUN, as well as in carcass performance.

ACKNOWLEDGMENTS

We would like to thank Evonik Nutrition & Care GmbH for financial support of this research. Appreciation is also expressed to DSM Nutritional Products for in-kind support as well

as Dr. Zhikai Zeng for assistance in statistical analysis.

Conflict of interest statement: None.

LITERATURE CITED

AOAC. 2007. Official methods of analysis of AOAC International. 18th ed. AOAC International, Gaithersburg, MD.

Apple, J. K., C. V. Maxwell, D. C. Brown, K. G. Friesen, R. E. Musser, Z. B. Johnson, and T. A. Armstrong. 2004. Effects of dietary lysine and energy density on performance and carcass characteristics of finishing pigs fed ractopamine. J. Anim. Sci. 82:3277–3287. doi:10.2527/2004.82113277

Coma, J., D. Carrion, and D. R. Zimmerman. 1995. Use of plasma urea nitrogen as a rapid response criterion to determine the lysine requirement of pigs. J. Anim. Sci. 73:472–481. doi:10.2527/1995.732472x

Commission Directive. 1998. Establishing community methods for 434 the determination of amino acids, crude oils and fats, and olan-quindox in feeding stuff and amending Directive 71/393/EEC, annex part A. Determination of Amino Acids. Offic. J. Eur. Commis. L257:14–23.

Commission Directive. 2000. Establishing community methods for the determination of vitamin A, vitamin E and tryptophan, annex part C. Determination of tryptophan. Offic. J. Eur. Commis. L174:45–50.

Elsbernd, A. J., C. F. de Lange, K. J. Stalder, L. A. Karriker, and J. F. Patience. 2017. SID lysine requirement of immunologically and physically castrated male pigs during the grower, early and late finisher periods. J. Anim. Sci. 95:1253–1263. doi:10.2527/jas.2016.0544

Goodband, R. D., J. L. Nelssen, R. H. Hines, D. H. Kropf, R. C. Thaler, B. R. Schricker, G. E. Fitzner, and A. J. Lewis. 1990. The effects of porcine somatotropin and dietary lysine on growth performance and carcass characteristics of finishing swine. J. Anim. Sci. 68:3261–3276. doi:10.2527/1990.68103261x

Grandhi, R. R., and R. L. Cliplef. 1997. Effects of selection for lower backfat, and increased levels of dietary amino acids to digestible energy on growth performance, carcass merit and meat quality in boars, gilts, and barrows. Can. J. Anim. Sci. 77:487–496. doi:10.4141/a96-133

Heo, J. M., J. C. Kim, C. F. Hansen, B. P. Mullan, D. J. Hampson, and J. R. Pluske. 2009. Feeding a diet with decreased protein content reduces indices of protein fermentation and the incidence of postweaning diarrhea in weaned pigs challenged with an enterotoxigenic strain of Escherichia coli. J. Anim. Sci. 87:2833–2843. doi:10.2527/jas.2008-1274

Htoo, J. K., J. P. Oliveira, L. F. T. Albino, M. I. Hannas, N. A. A. Barbosa, and H. S. Rostagno. 2016. Bioavailability of L-lysine HCl and L-lysine sulfate as lysine sources for growing pigs. J. Anim. Sci. 94:253–256. doi:10.2527/jas.2015-9797

Jones, C. K., M. D. Tokach, J. L. Usry, C. R. Neill, and J. F. Patience. 2014. Evaluating lysine requirements of nursery pigs fed low protein diets with different sources of nonessential amino acids. J. Anim. Sci. 92:3460–3470. doi:10.2527/jas.2014-7018

Knowles, T. A., L. L. Southern, K. R. Robbins, R. Buresh, and A. Brundage. 1997. The use of serum urea nitrogen concentrations for the determination of lysine requirements of gilts. Professional Anim. Scientist. 13:65–69. doi:10.15232/s1080-7446(15)31847-7

Kohn, R. A., M. M. Dinneen, and E. Russek-Cohen. 2005. Using blood urea nitrogen to predict nitrogen excretion and efficiency of nitrogen utilization in cattle, sheep, goats, horses, pigs, and rats. J. Anim. Sci. 83:879–889. doi:10.2527/2005.834879x

Littell, R., P. Henry, A. Lewis, and C. Ammerman. 1997. Estimation of relative bioavailability of nutrients using SAS procedures. J. Anim. Sci. 75: 2672–2683. doi:10.2527/1997.75102672x

Llames, C. R., and J. Fontaine. 1994. Determination of amino acids in feeds: collaborative study. J. Assoc. Off. Anal. Chem. 77:1362–1402.

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

Palencia, J. Y. P., M. Resende, M. A. G. Lemes, M. F. S. A. Mendes, S. R. Silva, Júnior, L. Otani, A. P. Schinckel, M. L. T. Abreu, and V. S. Cantarelli. 2019. Relative bioavailability of l-lysine sulfate is equivalent to that of l-lysine HCl for nursery piglets. J. Anim. Sci. 97:269–278. doi:10.1093/jas/sky394

Pogge, D., M. Drewnoski, and S. Hansen. 2014. High dietary sulfur decreases the retention of copper, manganese, and zinc in steers. J. Anim. Sci. 92: 2182–2191. doi:10.2527/jas.2013-7481

Smiricky-Tjardes, M. R., I. Mavromichalis, D. M. Albin, J. E. Wubben, M. Rademacher, and V. M. Gabert. 2004. Bioefficacy of L-lysine sulfate compared with feed-grade L-lysine-HCl in young pigs. J. Anim. Sci. 82:2610–2614. doi:10.2527/2004.8292610x

Witte, D. P., M. Ellis, F. K. McKeith, and E. R. Wilson. 2000. Effect of dietary lysine level and environmental temperature during the finishing phase on the intramuscular fat content of pork. J. Anim. Sci. 78:1272–1276. doi:10.2527/2000.7851272x