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Non Ruminant Nutrition

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Nutritional evaluation of different varieties of sorghum and the effects on nursery pig growth performance

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Abstract

Five experiments were conducted to determine the standardized total tract digestibility (**STTD**) of P, digestible energy (**DE**), metabolizable energy (**ME**), and standardized ileal digestibility (**SID**) of amino acids (**AA**) in three sorghum varieties compared with corn and to determine the effects of sorghum varieties on nursery pig growth. In exp. 1, 48 barrows (initially 18.6 kg) were housed individually in metabolism crates. Treatments were arranged in a 2 × 4 factorial evaluating two levels of microbial phytase (0 or 500 units/kg) and four grain sources (corn, high-lysine, red, or white sorghum). Added phytase improved ($P < 0.05$) STTD of P in all ingredients, but was not different among the grains. In exp. 2, the DE and ME in the three sorghum varieties were not different from corn. In exp. 3, 10 growing barrows (initially 25.9 kg) with a T-cannula in the terminal ileum were used. Standardized ileal digestible Lys, Met, Thr, and Val were greater ($P < 0.05$) in corn than in the sorghum-based diets with no differences among the sorghum varieties. In exp. 4, 160 pigs (initially 6.3 kg) were randomly allotted to one of four dietary treatments with five pigs per pen and eight replicate pens per treatment in a 20-d experiment. Dietary treatments included corn or the three sorghum varieties, where the varieties of sorghum replaced corn on an SID Lys basis. No differences among treatments were observed in any growth performance parameters. In exp. 5, treatments consisted of a corn-based diet, a diet based on conventional sorghum (a mixture of red and white sorghum), and four diets with high-lysine sorghum containing increasing amounts of feed-grade AA, replacing soybean meal. Overall, pigs fed the high-lysine sorghum diet with the greatest amount of added feed-grade AA had the poorest gain:feed ratio (**G:F**; $P < 0.05$) compared with pigs fed all the other experimental diets. Within those fed the high-lysine sorghum and feed-grade AA, average daily gain, final body weight (linear, $P < 0.10$), and G:F (linear, $P < 0.01$) decreased as feed-grade AA increased. In summary, no differences in STTD of P or in DE and ME were observed among the grain sources. The SID AA values for the three sorghum varieties were not different; however, they were all lower than for corn. These results indicate that these varieties of sorghum can successfully replace corn in nursery pig diets if diets are formulated to account for differences in AA digestibility.

Key words: corn, feed-grade amino acids, high-lysine sorghum, nursery pigs

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Abbreviations

AA	amino acids
ADFI	average daily feed intake
ADG	average daily gain
AEE	acid hydrolyzed ether extract
ATTD	apparent total tract digestibility
BW	body weight
CP	crude protein
DAA	dispensable AA
DE	digestible energy
DM	dry matter
DMI	dry matter intake
EPL	endogenous P loss
G:F	gain-to-feed ratio
GE	gross energy
IAA	indispensable AA
ME	metabolizable energy
ND	not detected
NE	net energy
SBM	soybean meal
SID	standardized ileal digestibility
STTD	standardized total tract digestibility

Introduction

Among the cereal grains, corn is the most commonly used in swine diets in the United States; however, sorghum is also an excellent energy source and can be used as a complete or partial replacement for corn (Stein et al., 2016). Results of previous research indicate that sorghum can successfully replace corn in nursery pig diets with minimal differences observed in growth performance (Fialho et al., 2004; Sotak et al., 2014; Goodband et al., 2016). Depending on the variety, crude protein (**CP**) content of sorghum may vary from 6.8% to 19.6% and can have high concentrations of indispensable amino acids (**AA**; Hulse et al., 1980; Subramanian et al., 1990). This indicates that specific varieties of sorghum can not only replace corn but also can be included in diets supplemented with feed-grade AA and replace a portion of soybean meal (SBM), potentially lowering diet cost. However, when fed to nonruminants, specific varieties of sorghum may have reduced nutritional value compared with corn (Khoddami et al., 2015), thereby having negative effects on growth performance.

The nutritional value of sorghum is reduced in varieties with high tannin content, because tannins are antinutritional factors. Tannins are plant secondary metabolites, which may inhibit enterocyte metabolism, amylase activity, and have the ability to form complexes with dietary protein and thereby reduce sugar and AA absorption (Butler et al., 1984; Karasov et al., 1992). Corn and sorghum also contain phytate, which consists of one myo-inositol molecule and six molecules of inorganic phosphate (Birgit et al., 2002). Pigs do not synthesize adequate amounts of endogenous phytase to liberate the P in phytate and the phytate bound P. As a result, it is not available for absorption and is the reason for the low digestibility of Ca and P in sorghum (Birgit et al., 2002; Liao et al., 2005). If microbial phytase is not provided in the diet, P and Ca absorption and utilization may be compromised (Pallauf et al., 1994).

The breeding of sorghum has generated new varieties selected to have reduced concentrations of anti-nutritional factors (Stein et al., 2016). One of these new varieties was predicted to have greater concentrations of AA, specifically lysine, compared with conventional varieties. However, there are no data for effects of adding phytase to diets containing sorghum and no data to demonstrate the nutritional value of this specific variety of high-lysine sorghum and the effect of nursery pig growth performance. Therefore, the first objective of this study was to determine the nutritional value of high-lysine sorghum compared with conventional sorghum varieties and corn based on standardized total tract digestibility (**STTD**) of P with the inclusion of microbial phytase (exp. 1), digestible energy (**DE**) and metabolizable energy (**ME**; exp. 2), and standardized ileal digestibility (**SID**) of AA (exp. 3). The second objective was to compare nursery pig growth performance among the different grain sources (exp. 4) as well as the effect of high-lysine sorghum and increasing additions of feed-grade AA on nursery pig growth performance (exp. 5). The hypothesis was that if diets are formulated to be balanced in SID AA and STTD P, then growth performance of pigs will not be influenced by inclusion of sorghum in the diets.

Materials and Methods

General

The University of Illinois and Kansas State University Institutional Animal Care and Use Committees approved the protocols used in these experiments. Experiments 1, 2, 3, and 4 were conducted at the University of Illinois (Urbana-Champaign) Swine Research Center and exp. 5 was conducted at the Kansas State University Swine Teaching and Research Center in Manhattan, KS. One batch of corn, high-lysine sorghum, red sorghum, and white sorghum was obtained and ground to 500 microns at Kansas State University and shipped to the Swine Research Center at the University of Illinois at Urbana-Champaign, IL. Multiple samples were collected from each ingredient, homogenized, and then subsampled for analysis (Table 1).

Experiment 1: phosphorus digestibility

Experiment 1 was designed to determine the apparent total tract digestibility (**ATTD**) of Ca and P, as well as STTD of P in corn, high-lysine sorghum, red sorghum, and white sorghum. A total of 48 growing barrows (initially 18.6 kg; Line 359 × Camborough; PIC, Hendersonville, TN) were randomly allotted to one of eight dietary treatments in a complete randomized design with six replicate pigs per diet. Dietary treatments were arranged in a 2 × 4 factorial design with two levels of microbial phytase (0 or 500 units/kg; Quantum Blue 5G; AB Vista, Marlborough, UK) and four grain sources (corn, high-lysine, red, or white sorghum). All diets were formulated to meet or exceed current vitamin and mineral requirement estimates (NRC, 2012), except P which was approximately 50% of its requirement estimate (Table 2).

Pigs were placed in individual metabolism crates that were equipped with a self-feeder, a nipple waterer, and slatted floors to allow for total collection of feces. All diets were fed in meal form. Pigs were limit fed at three times the energy requirement for maintenance (i.e., 197 kcal ME/kg × $BW^{0.60}$; NRC, 2012), which was provided each day in two equal meals at 0800 and 1700 hours. Throughout the study, pigs had free access to water. Feed consumption was recorded daily and diets were fed for 12 d. The initial 5 d was considered the adaptation period to the diet, whereas fecal material was collected during the following 4 d according to standard procedures using the marker-to-marker approach (Adeola, 2001).

Fecal samples were stored at −20 °C immediately after collection. Fecal samples were thawed at the conclusion of

Table 1. Chemical analysis of yellow dent corn and different sources of sorghum (as-fed basis)[1]

Item	Corn	Sorghum varieties		
		High-lysine	Red	White
Dry matter, %	85.65	89.31	87.59	87.41
Gross energy, kcal/kg	3,740	3,959	3,827	3,794
Crude protein, %	6.46	13.92	9.49	8.38
AEE, %	4.52	3.50	3.20	4.04
Insoluble dietary fiber, %	11.70	11.90	10.10	10.70
Soluble dietary fiber, %	0.20	0.10	0.40	0.20
Total dietary fiber, %	11.90	12.00	10.50	10.90
Ash, %	1.18	1.66	1.72	1.33
Calcium, %	0.03	0.02	0.02	0.01
Total phosphorus, %	0.26	0.35	0.32	0.30
Phytic acid, %	0.69	0.97	0.88	0.81
Phytate bound P[2], %	0.19	0.27	0.25	0.23
Nonphytate P[3], %	0.07	0.08	0.07	0.07
Phytase, FTU[4]/kg	<70	<70	<70	<70
Tannic acid, %	—	0.08	0.13	0.11
Carbohydrates				
Glucose, %	0.44	0.34	0.40	0.39
Sucrose, %	1.45	0.77	0.37	0.63
Maltose, %	0.11	0.05	0.14	0.08
Fructose, %	0.25	0.18	0.11	0.12
Stachyose, %	ND[5]	0.06	ND	ND
Raffinose, %	0.15	0.10	ND	0.08
Starch, %	59.12	57.74	62.40	62.46
Minerals				
K, %	0.32	0.39	0.28	0.33
Mg, %	0.10	0.15	0.14	0.13
Na, mg/kg	49.00	35.00	7.00	7.00
S, %	0.11	0.14	0.10	0.09
Cl, %	<0.10	<0.10	<0.10	<0.10
Cu, mg/kg	2.00	5.00	2.00	2.00
Fe, mg/kg	35.00	38.00	38.00	36.00
Mn, mg/kg	8.00	15.00	14.00	16.00
Se, mg/kg	0.40	<0.20	0.60	0.30
Zn, mg/kg	21.00	26.00	20.00	20.00
Indispensable AA, %				
Arginine	0.33	0.43	0.35	0.28
Histidine	0.20	0.31	0.23	0.18
Isoleucine	0.25	0.62	0.41	0.36
Leucine	0.76	2.08	1.29	1.15
Lysine	0.28	0.26	0.24	0.20
Methionine	0.14	0.19	0.16	0.16
Phenylalanine	0.32	0.80	0.52	0.44
Threonine	0.24	0.42	0.32	0.27
Tryptophan	0.07	0.11	0.09	0.09
Valine	0.32	0.71	0.51	0.43
Dispensable AA, %				
Alanine	0.47	1.38	0.89	0.80
Aspartic acid	0.48	0.94	0.65	0.58
Cysteine	0.16	0.24	0.19	0.16
Glutamic acid	1.19	3.16	1.98	1.76
Glycine	0.27	0.38	0.32	0.27
Serine	0.31	0.54	0.40	0.35
Tyrosine	0.19	0.38	0.28	0.22
All AA	6.70	14.39	9.85	8.61

[1] Multiple samples were collected from each ingredient, homogenized, and then subsampled for analysis at the University of Illinois (Urbana, IL) and the University of Missouri Agricultural Experiment Station Chemical Laboratory (Columbia, MO) for AA analysis performed in duplicate.
[2] Calculated as 28.2% of phytic acid (Tran and Sauvant, 2004).
[3] Calculated as total P – phytate P.
[4] FTU = phytase units.
[5] ND, not detected.

the experiment and mixed within pig and diet, and then dried in a 50 °C forced air drying oven and ground through a 1-mm screen in a Wiley mill (model 4; Thomas Scientific, Swedesboro, NJ) prior to analysis. Fecal and diet samples were analyzed for DM (method 930.15; AOAC International, 2007) and ash (method 942.05; AOAC International, 2007), and Ca and P were analyzed by inductively coupled plasma optical emission spectrometry using an internally validated method (method 985.01 A, B, and C; AOAC International, 2007) after wet ash sample preparation (method 975.03 B(b); AOAC International, 2007). Ingredients were analyzed for Ca and P and other minerals as explained for diets. Analyses for minerals were analyzed in triplicate and were conducted at the Agricultural Experiment Station Chemical Laboratories at the University of Missouri (Columbia, MO). Ingredients were also analyzed for phytic acid (Ellis et al., 1977), and diets were analyzed for phytase activity (method 2000.012; AOAC International, 2007). The ATTD of P in each source of cereal grain was calculated. By correcting these values for the basal endogenous losses of P (i.e., 190 mg/kg dry matter intake; **DMI**), values for the STTD of P in each cereal grain both without and with added phytase were calculated (NRC, 2012).

Experiment 2: energy measurements

Experiment 2 was conducted to determine the ATTD of GE and the DE and ME in the four grain sources used in exp.1. A total of 32 growing barrows (initially 18.5 kg; Line 359 × Camborough; PIC, Hendersonville, TN) were randomly allotted to one of four dietary treatments in a complete randomized design with eight replicate pigs per diet. The four diets each contained one of the four grain sources as the only energy-containing ingredient (Table 3). All diets were formulated to meet or exceed current vitamin and mineral requirement estimates (NRC, 2012).

Pigs were housed individually in metabolism crates that were equipped with a self-feeder, a nipple waterer, and a slatted floor. A screen and a urine pan were placed under the slatted floor to allow for the total, but separate, collection of urine and fecal materials. Pigs were fed at three times the energy requirement for maintenance (i.e., 197 kcal ME/kg × $BW^{0.60}$), which was provided each day in two equal meals at 0800 and 1600 hours. Throughout the study, pigs had ad libitum access to water. Each period lasted 12 d. The initial 5 d was considered the adaptation period to the diet, whereas urine and fecal material were collected during 4 d according to standard procedures using the marker-to-marker approach. Urine was collected in urine buckets over a preservative of 50 mL of hydrochloric acid. Fecal samples and 10% of the collected urine were stored at −20 °C immediately after collection. At the conclusion of the experiment, urine samples were thawed and mixed within animal and diet, and a subsample was lyophilized before analysis (Kim et al., 2009).

Fecal samples were thawed and mixed within pig and diet, and then dried in a 50 °C forced air drying oven prior to analysis. Ingredients and diets were analyzed for DM and ash as explained for exp. 1. Ingredients, diets, fecal, and urine samples were analyzed for GE using bomb calorimetry (model 6400; Parr Instruments, Moline, IL). Ingredients were analyzed for CP using the combustion procedure (method 990.03; AOAC International, 2007) and for acid hydrolyzed ether extract (**AEE**) by acid hydrolysis using 3N HCl (Ankom HCl Hydrolysis System, Ankom Technology, Macedon, NY) followed by fat extraction (Ankom XT-15 Extractor, Ankom Technology). Ingredients were also analyzed for insoluble dietary fiber and soluble dietary fiber according to method 991.43 (AOAC International, 2007) using the Ankom$^{\text{TDF}}$ Dietary Fiber Analyzer (Ankom Technology). Total dietary fiber was calculated as the sum of insoluble dietary fiber and soluble dietary fiber. Starch was

Table 2. Diet composition and chemical analysis, exp. 1[1]

	No phytase				500 FTU[2]/kg phytase			
		Sorghum varieties				Sorghum varieties		
Item	Corn	High-lysine	Red	White	Corn	High-lysine	Red	White
Corn	95.65	—	—	—	—	—	—	95.64
Red sorghum	—	—	95.65	—	—	95.64	—	—
White sorghum	—	—	—	95.65	—	—	95.64	—
High-lysine sorghum	—	95.65	—	—	95.64	—	—	—
Soybean oil	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Limestone	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Phytase[2]	—	—	—	—	0.01	0.01	0.01	0.01
Vitamin–mineral premix[3]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Analyzed values[4]								
Dry matter, %	86.32	89.49	87.94	87.65	89.43	87.95	87.92	86.73
Ash, %	2.34	2.75	2.30	2.43	2.64	2.84	2.33	2.30
Calcium, %	0.31	0.34	0.32	0.29	0.36	0.37	0.29	0.36
Phosphorus, %	0.26	0.35	0.32	0.28	0.35	0.31	0.27	0.27
Phytase, FTU/kg	<70	<70	<70	<70	700	670	740	760

[1] A total of 48 growing barrows (initially 18.6 kg; Line 359 × Camborough; PIC, Hendersonville, TN) were randomly allotted to one of eight dietary treatments in a randomized complete block design with six replicate pigs per diet.

[2] The phytase premix (Quantum Blue 5G; AB Vista, Marlborough, UK) contains 5,000 phytase units per gram. At 0.01% inclusion, the premix was calculated to provide 500 units of phytase per kilogram in the complete diet; FTU = phytase units.

[3] Provided the following quantities of vitamins and micro-minerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,150 IU; vitamin D_3 as cholecalciferol, 2,210 IU; vitamin E as selenium yeast, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.42 mg; thiamin as thiamine mononitrate, 1.10 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 1.00 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.6 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 125 mg as iron sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.30 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc hydroxychloride.

[4] Multiple samples were collected from each diet, homogenized, and then subsampled for analysis at the University of Illinois (Urbana, IL).

analyzed in all ingredients using the glucoamylase procedure (method 979.10; AOAC International, 2007). Glucose, fructose, maltose, sucrose, stachyose, and raffinose were analyzed in all ingredients by extracting and quantifying the sugars using high-performance liquid chromatograpy and a pulsed amperometric detector (Dionex) as described by Cervantes-Pahm and Stein (2010). Tannic acid was analyzed in high-lysine sorghum, red sorghum, and white sorghum as described by Taylor et al. (2007).

Following analysis, the ATTD of GE and DM was calculated for each diet, and the DE and ME in each diet were calculated as well (Adeola, 2001). The DE and ME of each source of sorghum or of corn were calculated by dividing the DE and ME of the diet by the inclusion rate of sorghum or corn in that diet.

Experiment 3: ileal digestibility

The objective of exp. 3 was to determine the SID of AA in the four grain sources. Ten growing barrows (initially 25.9 kg; Line 359 × Camborough; PIC, Hendersonville, TN) were fitted with a T-cannula in the distal ileum and were randomly allotted to one of five test diets in a 5-period design with 2 replicate pigs per diet in each period for a total of 10 replicates per diet. The first diet contained 94.0% corn, and the other diets contained 94.2% of a high-lysine sorghum, red sorghum, or white sorghum. In each of these diets, corn or sorghum was the only source of AA (Table 4). The fifth diet was a N-free diet that was used for determining basal AA endogenous losses from the small intestine. All diets were formulated to meet or exceed current vitamin and mineral requirement estimates (NRC, 2012) and contained 0.40% chromic oxide as an indigestible marker. Complete diet samples were obtained and stored for later analysis.

Pigs were housed individually in pens (1.2 × 1.5 m) equipped with a nipple drinker that allowed for unlimited access to water. Pens had smooth sides and fully slatted tribar floors. Each pig was weighed at the beginning of each period before being fed the next dietary treatment to determine the amount of feed needed per day at a level 3.2 times the estimated maintenance requirement (i.e., 197 kcal ME per kg BW$^{0.6}$; NRC, 2012) for energy. Pigs were also weighed at the conclusion of the experiment. Daily feed allocation was recorded. Each period consisted of a 5-d adaptation, and a supplemental AA mixture was added to the diets during this period. On days 6 and 7, the supplemental AA mixture was not provided and dietary treatments were the only source of AA. Ileal digesta collection occurred on days 6 and 7 for 8 h each day. Digesta samples were collected by attaching a plastic bag to the cannula barrel and digesta flowing into the bag was collected. The plastic bags were removed every 30 min or as soon as they became full. Thereafter, the collected samples were immediately frozen at −20 °C to prevent any bacterial degradation of the AA in the digesta. Feed was withdrawn at the end of each period before giving the next experimental diet the following morning to avoid any carryover effects.

At the conclusion of the experiment, digesta samples from each pig were thawed, mixed within animal and diet, and a subsample was lyophilized and finely ground for chemical analysis. Digesta samples, grain ingredient samples, and complete diet samples were analyzed for DM (method 930.15; AOAC International, 2007), chromium, CP (method 990.03; AOAC International, 2007), and AA

Table 3. Diet composition and chemical analysis, exp. 2[1]

		Sorghum varieties		
Item	Corn	High-lysine	Red	White
Corn	97.75	—	—	97.75
Red sorghum	—	—	97.75	—
White sorghum	—	—	—	—
High-lysine sorghum	—	97.75	—	—
Dicalcium phosphate	1.10	1.10	1.10	1.10
Calcium carbonate	0.60	0.60	0.60	0.60
Salt	0.40	0.40	0.40	0.40
Vit-mineral premix[2]	0.15	0.15	0.15	0.15
Analyzed values[3]				
Dry matter, %	86.90	89.56	88.31	86.90
GE, kcal/kg	3,828	4,068	3,897	3,828

[1] A total of 32 growing barrows (initially 18.5 kg; Line 359 × Camborough; PIC, Hendersonville, TN) were randomly allotted to one of four dietary treatments in a randomized complete block design with eight replicate pigs per diet.

[2] The vitamin–micromineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,136 IU; vitamin D3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B12, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc hydroxychloride.

[3] Multiple samples were collected from each diet, homogenized, and then subsampled for analysis at the University of Illinois (Urbana, IL).

according to the AOAC procedures (AOAC International, 2007); apparent ileal digestibility (**AID**) and SID values were calculated based on the methods from the study of Stein et al. (2007).

Experiment 4: growth performance and diarrhea frequency from 6.3 to 10.4 kg

Experiment 4 was designed to determine effects of the four grain sources on growth performance and diarrhea frequency of weanling pigs. A total of 160 weaned pigs (approximately 21 d or age and initially 6.3 kg; Line 359 × Camborough; PIC, Hendersonville, TN) were randomly allotted to four dietary treatments with five pigs per pen and eight replicate pens per treatment. Pens were 1.20 × 1.35 m and provided 0.40 m^2 per pig.

Treatments consisted of diets formulated based on either corn, red, white, or high-lysine sorghum, where the varieties of sorghum replaced corn on an SID lysine basis (Table 5). Treatment diets were formulated and manufactured in two dietary phases (phase 1 = day 0 to 11 and phase 2 = day 11 to 20) and were formulated to meet current estimates for nutrient requirements (NRC, 2012) for 5 to 7 and 7 to 11 kg pigs, respectively.

Pigs were weighed individually and feed disappearance was recorded at the beginning of the experiment and at the conclusion of each phase to determine average daily gain (**ADG**), average daily feed intake (**ADFI**), and gain:feed (**G:F**). Diarrhea scores were assessed visually every other day using a score from 1 to 5 (1 = normal feces; 2 = moist feces; 3 = mild diarrhea; 4 = severe diarrhea; and 5 = watery diarrhea). Diarrhea frequency was obtained by totaling the number of pen days with diarrhea scores ≥ 3 divided by the total number of pen days multiplied by 100.

All diets were ground as explained for exp. 1 prior to chemical analysis. Diets were analyzed for DM, ash, GE, CP, and AEE as explained for exp. 1 and 2. Diets were also analyzed for AA on a Hitachi AA Analyzer (model no. L8800; Hitachi High Technologies America, Inc., Pleasanton, CA) using ninhydrin for postcolum derivatization and norleucine as the internal standard (method 982.30 E [a, b, c]; AOAC International, 2007), and Ca and P were analyzed as explained for exp. 1.

Experiment 5: effect of high-lysine sorghum on nursery pig performance from 9.6 to 20.9 kg

Experiment 5 was designed to determine the effect of high-lysine sorghum and increasing additions of feed-grade AA on nursery pig growth. At weaning, approximately 21 d of age, 300 pigs were moved to the nursery and randomly allotted to pens of five based on initial body weight (**BW**). Pigs were fed a common diet for 20 d after weaning. On day 20 after weaning, considered day 0 in the trial, a total of 293 pigs (initially 9.7 kg; Line 241 × 600; DNA, Columbus, net energy [**NE**]) were allotted to a 20-d growth trial where pens were randomly assigned to one of six dietary treatments with 10 pens (blocks) per treatment. Each pen (1.2 × 1.5 m) contained a four-hole, dry, self-feeder and a nipple waterer to provide ad libitum access to feed and water.

Experimental treatments included a corn-based diet, a diet based on conventional sorghum, and four diets containing high-lysine sorghum. The corn-based, conventional sorghum, and the first high-lysine sorghum (low) diets were formulated to contain the same amount of SBM, each with varying amounts of feed-grade AA. The three remaining high-lysine diets (low-med, med-high, and high) included incrementally increasing amounts of feed-grade AA, at the expense of SBM. The diet formulation consisted of adding feed-grade AA such that each successive diet was balanced to the next limiting AA. Corn and SBM were analyzed for AA as explained for exp. 3 and CP (method 982.30 E(a); AOAC 2007) by the University of Missouri Agricultural Experiment Station Chemical Laboratory (Columbia, MO), and diets were formulated from these values. The conventional sorghum used in this study was a 50:50 blend of red and white and an average of the analyzed AA values was used in formulation. Diets with conventional sorghum varieties and high-lysine sorghum were formulated based on the SID results obtained in exp. 3. Corn and SBM in treatment diets

Table 4. Diet composition, exp. 3 (as-fed basis)[1,2]

		Sorghum varieties			
Item	Corn	High-lysine	Red	White	N-free
Ingredient, %					
Corn	94.00	—	—	—	—
Red sorghum	—	—	94.20	—	—
White sorghum	—	—	—	94.20	—
High-lysine sorghum	—	94.20	—	—	—
Soybean oil	3.00	3.00	3.00	3.00	4.00
Solka floc	—	—	—	—	4.00
Dicalcium phosphate	1.20	1.10	1.10	1.10	1.65
Calcium carbonate	0.70	0.60	0.60	0.60	0.35
Cornstarch	—	—	—	—	68.30
Sucrose	—	—	—	—	20.00
Chromic oxide	0.40	0.40	0.40	0.40	0.40
Magnesium oxide	—	—	—	—	0.10
Potassium carbonate	—	—	—	—	0.40
Salt	0.40	0.40	0.40	0.40	0.40
Vitamin–mineral premix[3]	0.30	0.30	0.30	0.30	0.30
Total	100.00	100.00	100.00	100.00	100.00

[1] Ten growing barrows (initially 25.9 kg) were fitted with a T-cannula in the distal ileum and were randomly allotted to one of five test diets in a 5-period design with 2 replicate pigs per diet in each period for a total of 10 replicates per pig diet.

[2] One hundred grams of the following AA mixture (%) was supplemented to dietary treatments daily, during the adaptation period (initial 5 d): 57.92 glycine, 13.51 L-lysine HCl, 4.44 DL-methionine, 5.79 L-threonine, 1.35 L-tryptophan, 4.25 L-isoleucine, 4.83 L-valine, 2.12 L-histidine, and 5.79 L-phenylalanine.

[3] The vitamin–micromineral premix provided the following quantities of vitamins and microminerals per pound of complete diet: vitamin A as retinyl acetate, 11,128 IU; vitamin D_3 as cholecalciferol, 2,204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfite, 0.644 mg; thiamin as thiamine mononitrate, 0.109 mg; riboflavin, 2.985 mg; pyridoxine as pyridoxine hydrochloride, 0.109 mg; vitamin B_{12}, 0.014 mg; D-pantothenic acid as D-calcium pantothenate, 10.659 mg; niacin as nicotinamide and niacotinic acid, 19.958 mg; folic acid, 0.717 mg; biotin, 0.199 mg; Cu, 4.536 mg as copper sulfate; Fe, 56.699 mg as iron sulfate; I, 0.572 mg as potassium iodate; Mn, 27.216 mg as manganese sulfate; Se, 0.136 mg as sodium selenite; and Zn, 45.359 mg as zinc oxide.

were formulated using SID coefficients from NRC (2012). All diets were fed in meal form and formulated to the same Lys:NE ratio (Table 6), using NRC (2012) NE values for all ingredients. Treatments were fed for 20 d. Each pen was equipped with a 4-hole, dry self-feeder and nipple waterer to provide ad libitum access to feed and water. Pens of pigs were weighed and feed disappearance was recorded on days 0, 7, 14, and 20 to determine ADG, ADFI, and G:F.

Experimental diets were manufactured at the Kansas State University O.H. Kruse Feed Technology Innovation Center, Manhattan, KS. Complete diet samples were taken from five feeders per dietary treatment three times throughout the study. Samples were stored at −20 °C until they were homogenized, subsampled, and submitted to a commercial laboratory (Ward Laboratories, Inc., Kearney, NE) for analysis of DM (method 935.29; AOAC International, 2012), CP (AOAC 900.03, 2012), Ca, and P (method 968.08 b; AOAC International, 2012; for preparation using ICAP 6500, ThermoElectron Corp., Waltham, MA), ether extract (method 920.39 a; AOAC 2012; for preparation and ANKOM XT20 Fat Analyzer; Ankom Technology), and ash (method 942.05 a; AOAC, 2012). In addition, AA analysis was evaluated at the University of Missouri Agricultural Experiment Station Chemical Laboratory (Columbia, MO). Samples were analyzed in duplicate.

Statistical analysis

In exp. 1 and 2, data were analyzed as a randomized complete block using the MIXED procedure of SAS (SAS Institute Inc., Cary, NC) with the pig as the experimental unit. In exp. 1, the model included source of cereal grain, phytase, and the interaction between source of cereal grain and phytase as the main effects. Replicate was the random effect. In exp. 2, diet or ingredient was the fixed effect and replicate was the random effect. Least squares means were calculated using an least squares difference test, and if the model was significant, means were separated using the PDIFF statement. In exp. 3, the data were analyzed using the PROC MIXED procedure of SAS. The model included grain source as a fixed effect and pigs and period as random effects. In exp. 4, data were analyzed using the MIXED Procedure of SAS with the pen as the experimental unit. Least squares means were calculated and means were separated as explained for exp. 1. The chi-squared test was used to analyze frequency of diarrhea among treatments. In exp. 5, data were analyzed as a randomized complete block design using the GLIMMIX procedure of SAS, version 9.4, with pen as the experimental unit. Initial weight (blocking factor) was included in the model as a random effect. Linear and quadratic effects of decreasing CP in high-lysine sorghum diets were evaluated and developed using the IML procedure of SAS, generating coefficients for unequally spaced treatments. Estimated means and corresponding standard errors (**SEM**) are reported. Pairwise comparisons were conducted using a Tukey's adjustment to prevent inflation of type I error due to multiple comparisons. Degrees of freedom were estimated using the Kenward–Rogers approach. All results were considered significant at $P \leq 0.05$ and tendencies between $P > 0.05$ and $P \leq 0.10$.

Results

General

The concentration of P in corn and in red and white sorghum varieties was between 0.26% and 0.32%, but high-lysine sorghum

Table 5. Diet composition and chemical analysis, exp. 4[1]

	Phase 1				Phase 2			
		Sorghum varieties				Sorghum varieties		
Item	Corn	High-lysine	Red	White	Corn	High-lysine	Red	White
Corn	43.00	—	—	—	48.82	—	—	—
Red sorghum	—	—	43.23	—	—	—	50.20	—
White sorghum	—	—	—	41.80	—	—	—	49.24
High-lysine sorghum	—	46.80	—	—	—	54.50	—	—
Soybean meal, 48% CP	24.25	20.25	24.00	25.50	26.00	20.00	24.50	25.50
Dried whey	20.00	20.00	20.00	20.00	15.00	15.00	15.00	15.00
Enzyme-treated SBM, HP 300	4.50	4.50	4.50	4.50	5.00	5.00	5.00	5.00
Blood plasma, spray dried	3.00	3.00	3.00	3.00	—	—	—	—
Soybean oil	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Limestone	1.17	1.16	1.20	1.18	1.02	1.04	1.07	1.05
Dicalcium phosphate	0.80	0.85	0.75	0.75	0.90	0.95	0.85	0.85
L-Lysine HCl	0.34	0.50	0.39	0.35	0.34	0.56	0.43	0.41
DL-Methionine	0.20	0.20	0.20	0.19	0.18	0.19	0.20	0.20
L-Threonine	0.09	0.09	0.08	0.08	0.09	0.11	0.10	0.10
Salt	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Vitamin–mineral premix[2]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Analyzed values[3]								
Dry matter, %	88.42	89.36	88.78	88.62	88.85	89.71	89.12	88.82
Ash, %	6.16	6.34	6.38	5.63	5.50	5.68	5.62	5.42
Gross energy, kcal/kg	3,945	4,025	3,990	3,956	4,010	4,082	4,022	4,001
Crude protein, %	23.00	24.07	23.58	24.94	22.09	22.56	22.26	21.97
AEE, %	3.04	2.82	2.40	3.12	4.84	3.53	3.26	4.06
Calcium, %	0.82	0.81	0.79	0.78	0.71	0.75	0.70	0.73
Phosphorus, %	0.63	0.66	0.62	0.62	0.59	0.66	0.61	0.61
Indispensable AA, %								
Arginine	1.29	1.27	1.29	1.31	1.23	1.19	1.18	1.20
Histidine	0.55	0.56	0.56	0.54	0.53	0.52	0.49	0.48
Isoleucine	1.00	1.08	1.05	1.05	0.99	1.05	0.97	0.98
Leucine	1.91	2.27	2.02	2.01	1.82	2.24	1.85	1.84
Lysine	1.61	1.62	1.63	1.49	1.44	1.38	1.41	1.44
Methionine	0.48	0.49	0.46	0.46	0.49	0.45	0.51	0.44
Methionine + Cysteine	0.88	0.93	0.86	0.85	0.84	0.81	0.82	0.78
Phenylalanine	1.07	1.19	1.12	1.12	1.05	1.15	1.02	1.02
Threonine	1.03	1.03	1.06	1.03	0.91	0.89	0.87	0.93
Tryptophan	0.31	0.30	0.28	0.32	0.27	0.26	0.26	0.27
Valine	1.12	1.20	1.19	1.17	1.05	1.11	1.00	1.01

[1] A total of 160 weaned pigs (initially 6.3 kg; Line 359 × Camborough; PIC, Hendersonville, TN) were randomly allotted to four dietary treatments with five pigs per pen and eight replicate pens per treatment

[2] Provided the following quantities of vitamins and micro-minerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,150 IU; vitamin D_3 as cholecalciferol, 2,210 IU; vitamin E as selenium yeast, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.42 mg; thiamin as thiamine mononitrate, 1.10 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 1.00 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.6 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 125 mg as iron sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.30 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc hydroxychloride.

[3] Multiple samples were collected from each diet, homogenized, and then subsampled for analysis at the University of Illinois (Urbana, IL).

contained 0.35% P (Table 1). Concentrations of phytate-bound and nonphytate-bound P were 0.27% and 0.08% in high-lysine sorghum, 0.25% and 0.07% in red sorghum, 0.23% and 0.07% in white sorghum, and 0.19% and 0.07% in corn, respectively. All cereal grains had intrinsic phytase activity of <70 FTU/kg.

Amino acid analysis of the grain sources indicated that high-lysine sorghum had greater concentrations of most AA compared with the other varieties of sorghum, but corn contained more Lys than all varieties of sorghum (Table 1). Crude protein was greatest for high-lysine sorghum, followed by red sorghum, white sorghum, and corn. The lysine in high-lysine sorghum was 0.26%, compared with 0.24%, 0.20%, and 0.28% in red sorghum, white sorghum, and corn, respectively.

Experiment 1: phosphorus digestibility

For P digestibility, there was no grain × phytase interaction for any of the response variables (Table 7). ADFI of pigs fed high-lysine sorghum tended to be less ($P < 0.10$) compared with pigs fed the red sorghum or corn, but was not different compared with pigs fed white sorghum. Pigs fed high-lysine sorghum had greater ($P < 0.05$) P intake compared with pigs fed white sorghum and had greater ($P < 0.05$) P in feces compared with pigs fed the other cereal grains. Pigs fed high-lysine sorghum also tended to have less ($P < 0.10$) basal endogenous P loss compared with pigs fed the red sorghum or corn. Pigs fed red sorghum had greater ($P < 0.05$) fecal and P output compared with pigs fed the other sorghum varieties or corn. However, no differences in ATTD or

Table 6. Diet composition, exp. 5, (as-fed basis)[1]

			Feed-grade AA levels in high-lysine sorghum diets			
Item	Corn	Sorghum	Low	Low-Med	Med-High	High
Ingredient, %						
Corn	59.55	—	—	—	—	—
Conventional sorghum	—	59.10	—	—	—	—
High-lysine sorghum	—	—	59.15	62.30	66.75	73.55
Soybean meal, 46.5% CP	34.70	34.65	34.65	31.70	27.50	21.05
Choice white grease	2.25	2.70	2.73	2.35	1.85	1.00
Calcium carbonate	0.95	0.96	0.96	0.96	0.94	0.93
Monocalcium phosphate, 21%	0.98	0.95	0.95	0.95	1.00	1.08
Salt	0.60	0.60	0.60	0.60	0.60	0.60
L-Lysine HCl	0.30	0.35	0.36	0.45	0.58	0.78
DL-Methionine	0.13	0.16	0.12	0.15	0.18	0.24
L-Threonine	0.12	0.13	0.08	0.12	0.17	0.25
L-Tryptophan	0.02	0.001	—	—	0.02	0.06
L-Valine	0.02	—	—	—	—	0.08
Trace mineral[2]	0.15	0.15	0.15	0.15	0.15	0.15
Vitamin premix[3]	0.25	0.25	0.25	0.25	0.25	0.25
Phytase[4]	0.02	0.02	0.02	0.02	0.02	0.02
Total	100.00	100.00	100.00	100.00	100.00	100.00
Calculated analysis						
SID AA, %						
Lysine	1.30	1.30	1.30	1.30	1.30	1.30
Isoleucine:lysine	64	66	74	71	66	59
Leucine:lysine	128	131	164	161	157	150
Methionine:lysine	33	34	32	33	34	36
Methionine and cysteine:lysine	56	56	56	56	56	56
Threonine:lysine	63	63	63	63	63	63
Tryptophan:lysine	19.1	19.2	20.1	19.0	19.0	19.1
Valine:lysine	70	69	77	74	70	70
SID lysine:net energy, g/Mcal	5.23	5.23	5.23	5.23	5.23	5.23
SID lysine:crude protein, g/kg	5.9	5.8	5.8	6.0	6.4	7.2
Total lysine, %	1.47	1.46	1.46	1.45	1.44	1.43
Net energy, kcal/kg	2,485	2,485	2,485	2,485	2,485	2,485
Crude protein, %	21.9	22.3	22.5	21.6	20.2	18.1
Calcium, %	0.73	0.73	0.73	0.72	0.71	0.70
Phosphorus, %	0.61	0.61	0.61	0.60	0.59	0.58
Available phosphorus, %	0.38	0.38	0.38	0.38	0.39	0.40

[1] Diets were fed from 9.7 to 20.9 kg BW, respectively.

[2] Provided per kilogram of premix: 22 g Mn from manganese oxide; 73 g Fe from iron sulfate; 73 g Zn from zinc sulfate; 11 g Cu from copper sulfate; 198 mg I from calcium iodate; and 198 mg Se from sodium selenite.

[3] Provided per kilogram of premix:3,527,360 IU vitamin A; 881,840 IU vitamin D3; 17,637 IU vitamin E; 3,307 mg riboflavin; 1,764 mg menadione; 11,023 mg pantothenic acid; 33,069 mg niacin; and 15.4 mg vitamin D12.

[4] HiPhos 2700 (DSM Nutritional Products, Parsippany, NJ) provided an estimated release of 0.10% STTD P.

STTD of P were observed among pigs fed the sorghum varieties or corn. Addition of phytase to diets did not affect ADFI, daily fecal output, or daily P intake. However, pigs fed diets with phytase had less ($P < 0.01$) daily fecal P output and reduced ($P < 0.05$) concentration of P in feces, which resulted in increased ($P < 0.01$) absorption of P, ATTD of P, and STTD of P. There was no effect of phytase addition on daily endogenous P loss.

For Ca intake, Ca in feces, Ca output, and ATTD of Ca, no grain × phytase interaction was observed. When phytase was not included in diets, daily amount of Ca absorbed was less in pigs fed red sorghum compared with pigs fed high-lysine sorghum or corn. However, when phytase was included in diets, pigs fed red sorghum had greater daily Ca absorption compared with pigs fed high-lysine sorghum (interaction; $P < 0.10$). Regardless of phytase addition, pigs fed corn had greater ($P < 0.01$) daily Ca intake compared with pigs fed high-lysine sorghum or white sorghum. Pigs fed high-lysine sorghum had greater ($P < 0.01$) concentration of Ca in feces compared with pigs fed red sorghum, and pigs fed red sorghum tended to have greater Ca output ($P < 0.10$) compared with pigs fed the other sorghum varieties. However, no differences in ATTD of Ca were observed among pigs fed the three sorghum varieties or corn. When phytase was added to diets, regardless of grain source, pigs had reduced ($P < 0.01$) concentration of Ca in feces and reduced ($P < 0.05$) daily Ca output, which resulted in an increase ($P < 0.01$) in Ca absorption and in ATTD of Ca.

Experiment 2: energy measurements

Pigs fed the red sorghum diet had greater ($P < 0.05$) fecal output and greater ($P < 0.05$) fecal GE output compared with pigs fed the white sorghum or corn diets (Table 8). This resulted in less ($P < 0.05$) DE and ME in the red sorghum diet compared with

Table 7. Effects of microbial phytase on P and Ca balance, ATTD, and STTD of P in high-lysine sorghum, red sorghum, white sorghum, and corn fed to growing pigs, exp. 1[1,2]

	No phytase				500 FTU[1]/kg phytase[3]							
		Sorghum varieties				Sorghum varieties				Probability, P-value <		
Item	Corn	High-lysine	Red	White	Corn	High-lysine	Red	White	SEM	Grain	Phytase	Grain × Phytase
ADFI, g	755	657	688	666	712	599	729	662	49	0.061	0.581	0.619
P intake, g/d	2.3	2.5	2.5	2.2	2.2	2.3	2.5	2.1	0.2	0.032	0.389	0.880
Fecal output, g/d	85.7	78.9	109.6	83.5	82.9	66.9	105.8	83.2	7.3	<0.001	0.267	0.783
P in feces %	1.7	2.2	1.7	1.9	0.9	1.6	1.1	1.2	0.1	<0.001	<0.001	0.581
P output, g/d	1.3	1.4	1.7	1.3	0.7	0.9	1.1	0.9	0.1	<0.001	<0.001	0.423
P absorption, g/d	1.0	1.1	0.8	0.9	1.4	1.4	1.4	1.1	0.2	0.182	<0.001	0.563
ATTD of P, %	41.5	41.9	28.1	38.5	66.2	62.3	56.1	53.9	4.8	0.280	<0.001	0.473
Basal EPL[4], mg/d	144	125	131	127	135	114	139	126	9.3	0.061	0.581	0.619
STTD of P[5], %	47.8	46.8	33.4	44.4	72.4	67.1	61.6	60.2	4.8	0.230	<0.001	0.480
Ca intake, g/d	2.8	2.5	2.5	2.2	3.0	2.4	3.0	2.2	0.19	<0.001	0.168	0.218
Ca in feces, %	1.3	1.3	1.1	1.2	0.7	1.1	0.7	0.8	0.09	0.007	<0.001	0.278
Ca output, g/d	0.9	0.8	1.1	0.8	0.5	0.6	0.6	0.6	0.07	0.070	<0.001	0.311
Ca absorption, g/d	1.8	1.6	1.4	1.4	2.4	1.8	2.3	1.6	0.19	0.005	<0.001	0.074
ATTD of Ca, %	65.6	64.7	56.2	62.1	81.5	74.8	79.0	73.4	3.0	0.185	<0.001	0.156

[1] A total of 48 growing barrows (initially 18.6 kg; Line 359 × Camborough; PIC, Hendersonville, TN) were randomly allotted to one of eight dietary treatments in a randomized complete block design with six replicate pigs per diet.
[2] Data are means of six observations per treatment.
[3] Phytase: Quantum Blue 5G (5,000 phytase units per gram; AB Vista, Marlborough, UK); FTU = phytase units.
[4] EPL, endogenous P loss. This value was estimated to be at 190 mg/kg DMI. The daily basal EPL (mg/d) for each diet was calculated by multiplying the EPL (mg/kg DMI) by the daily DMI of each diet (Almeida and Stein, 2010).
[5] Values for STTD were calculated by correcting values for ATTD for the basal endogenous loss of P (NRC, 2012).

Table 8. ATTD of energy, DE, and ME in experimental diets, exp. 2[1,2]

		Sorghum varieties				
Item	Corn	High-lysine	Red	White	SEM	Probability, P-value <
GE intake, kcal/d	3,089	3,303	3,319	3,461	245	0.554
Fecal output, g/d	67^{b}	87^{ab}	98^{b}	71^{b}	9	0.019
Fecal GE output, kcal/d	305^{b}	396^{ab}	458^{a}	339^{b}	38	0.021
Urine output, g/d	2,161	1,934	2,175	2,543	591	0.913
Urinary GE output, kcal/d	76	82	77	78	12	0.966
ATTD of GE, %	89.3^{a}	86.7^{b}	85.0^{b}	89.4^{a}	1.0	0.003
DE, kcal/kg	3,341^{ab}	3,433^{a}	3,252^{b}	3,389^{a}	39	0.004
ME, kcal/kg	3,240^{ab}	3,324^{a}	3,156^{b}	3,300^{a}	42	0.012
As-fed basis						
DE, kcal/kg	3,418^{ab}	3,512^{a}	3,327^{b}	3,467^{a}	40	0.004
ME, kcal/kg	3,315^{ab}	3,400^{a}	3,229^{b}	3,367^{a}	43	0.012
Dry matter basis						
DE, kcal/kg	3,992^{a}	3,934^{a}	3,800^{b}	3,968^{a}	46	0.007
ME, kcal/kg	3,871^{a}	3,809^{a}	3,687^{b}	3,864^{a}	49	0.014

[1] A total of 32 growing barrows (initially 18.5 kg; Line 359 × Camborough; PIC, Hendersonville, TN) were randomly allotted to one of four dietary treatments in a randomized complete block design with eight replicate pigs per diet.
[2] Data are least square means of eight observations for all treatments except for white sorghum ($n = 7$).
[a,b] Means within a row that do not have a common superscript differ, $P < 0.05$.

the high-lysine sorghum and white sorghum diets. The ATTD of GE in high-lysine sorghum and red sorghum (86.7% and 85.0%, respectively) were less ($P \leq 0.01$) than in white sorghum and corn (89.4% and 89.3%, respectively).

The DE and ME, on an as-fed basis, in corn were 3,418 and 3,315 kcal/kg, respectively. On an as-fed basis, these values were not different from the DE and ME values obtained for all sorghum varieties. However, values for DE and ME in red sorghum on an as-fed basis (3,327 and 3,229 kcal/kg, respectively) were less ($P < 0.05$) than in the other sorghum varieties. On a DM basis, values for DE and ME in red sorghum (3,800 and 3,687 kcal/kg, respectively) were also less ($P < 0.05$) than values for white sorghum, high-lysine sorghum, and corn.

Experiment 3: ileal digestibility

Chemical analysis of manufactured diets (Table 9) resulted in values consistent with formulation. There was no evidence for differences between pigs fed high-lysine sorghum and corn in AID values for CP, most total indispensable AA, and total dispensable AA ($P \geq 0.05$; Table 10). The AID values for Lys and Met were greater ($P < 0.05$) in corn than high-lysine sorghum; however, the AID of Trp was greater ($P < 0.05$) in high-lysine sorghum than in corn. When comparing the different varieties of conventional sorghum, AID of CP was greatest ($P < 0.05$) for high-lysine sorghum compared with red and white varieties of sorghum (Table 10). The AID values for His, Val, total indispensable AA, and total dispensable AA were greater ($P < 0.05$) in high-lysine sorghum compared with the other two varieties of conventional sorghum.

When accounting for endogenous N losses to determine SID values, digestibility of CP was greater for corn ($P < 0.05$; Table 11) compared with all varieties of sorghum. The SID values for most indispensable and dispensable AA were greater ($P < 0.05$; Table 11) in corn compared with each variety of sorghum. There was no evidence for differences in the SID coefficients for CP, leucine, lysine, methionine, phenylalanine, threonine, valine, and most dispensable AA when comparing high-lysine, red, and white sorghum varieties.

Experiment 4: growth performance and diarrhea frequency from 6.3 to 10.4 kg

No differences were observed in all growth performance parameters among pigs fed diets containing the four grain sources from day 0 to 11, 11 to 20, or for the entire experimental period (Table 12). Likewise, no differences among dietary treatments were observed in diarrhea scores and frequency of diarrhea.

Experiment 5: effect of high-lysine sorghum on nursery pig performance from 9.6 to 20.9 kg

Analysis of manufactured diets (Table 13) resulted in values consistent with formulation. Overall, there was no evidence for differences in ADG, ADFI, or final BW among all dietary treatments for the 20-d study (Table 14). Pigs fed the high-lysine sorghum with the low- and medium-low addition of feed-grade AA had increased ($P < 0.05$) G:F compared with pigs fed the high-lysine sorghum with the greatest feed-grade AA inclusion, with other treatments being intermediate; however, with the Tukey's adjustment, these differences were not significant.

When evaluating linear and quadratic effects of decreasing CP within the high-lysine sorghum diets, ADG tended to decrease with increasing feed-grade AA levels (linear, $P < 0.10$), resulting in marginal evidence for a reduction in final BW (linear, $P < 0.10$). Lastly, G:F worsened with increasing inclusion levels of feed-grade AA (linear, $P < 0.01$).

Discussion

Grain composition

Chemical analysis results for CP and DM of corn, red sorghum, and white sorghum used in these experiments agree with values previously reported (Sauvant et al., 2002; NRC, 2012; Cervantes-Pahm et al., 2014). The analyzed concentrations of ash, Ca, and P in sorghum varieties used in these experiments are in agreement with published values (NRC, 2012; Lopes et al., 2017). The analyzed values for ash, Ca, and P in corn are also in agreement

Table 9. Chemical analysis of diets, exp. 3 (%, as-fed basis)[1]

		Sorghum varieties			
Item	Corn	High-lysine	Red	White	N-free
Crude protein, %	7.10	13.24	8.78	7.80	0.41
Dry matter, %	87.51	90.12	87.64	88.23	94.45
Indispensable AA, %					
Arginine	0.35	0.40	0.31	0.29	0.01
Histidine	0.21	0.29	0.21	0.17	0.00
Isoleucine	0.26	0.58	0.38	0.33	0.01
Leucine	0.77	1.93	1.19	1.05	0.03
Lysine	0.29	0.24	0.22	0.20	0.01
Methionine	0.15	0.18	0.15	0.14	0.01
Phenylalanine	0.34	0.75	0.48	0.42	0.01
Threonine	0.26	0.40	0.29	0.26	0.01
Tryptophan	0.03	0.11	0.07	0.06	0.01
Valine	0.34	0.66	0.46	0.41	0.01
Dispensable AA, %					
Alanine	0.49	1.29	0.82	0.73	0.02
Aspartic acid	0.54	0.89	0.60	0.54	0.02
Cysteine	0.16	0.22	0.17	0.14	0.00
Glutamic acid	1.24	2.94	1.82	1.60	0.03
Glycine	0.30	0.36	0.30	0.27	0.01
Serine	0.31	0.50	0.37	0.32	0.01
Tyrosine	0.20	0.35	0.24	0.23	0.01
All AA	7.04	13.46	9.03	8.00	0.38

[1] Multiple samples were collected from each diet, homogenized, and then subsampled for analysis at Ward Laboratories, Inc. (Kearney, NE) for proximate analysis and the University of Missouri Agricultural Experiment Station Chemical Laboratory (Columbia, MO) for AA analysis performed in duplicate.

Table 10. Apparent ileal digestibility of AA in yellow dent corn and different varieties of sorghum[1]

		Sorghum varieties			
Item	Corn	High-lysine	Red	White	SEM
Crude protein, %	66.8^{ab}	70.1^{a}	60.4^{bc}	60.0^{c}	2.48
Indispensable AA, %					
Arginine	79.0^{a}	75.4^{ab}	70.7^{bc}	69.8^{c}	1.90
Histidine	80.2^{a}	74.4^{a}	65.0^{b}	65.0^{b}	3.06
Isoleucine	78.2^{a}	77.3^{ab}	71.5^{b}	71.1^{b}	2.60
Leucine	83.6^{a}	81.5^{ab}	75.8^{c}	77.6^{bc}	2.35
Lysine	63.3^{a}	46.1^{b}	42.3^{b}	43.7^{b}	3.72
Methionine	85.6^{a}	78.1^{b}	75.3^{b}	76.3^{b}	2.15
Phenylalanine	80.6^{a}	78.5^{ab}	73.2^{b}	73.9^{b}	2.51
Threonine	67.8^{x}	64.2^{xy}	58.1^{y}	55.8^{y}	3.87
Tryptophan	49.1^{b}	72.8^{a}	69.8^{a}	65.6^{a}	2.94
Valine	74.0^{a}	72.7^{a}	66.2^{b}	66.0^{b}	2.93
Total[2]	78.4^{a}	78.9^{a}	73.0^{b}	73.0^{b}	2.24
Dispensable AA, %					
Alanine	78.3^{x}	78.6^{x}	72.3^{y}	73.4^{xy}	2.28
Aspartic acid	77.3^{a}	73.3^{ab}	68.2^{bc}	66.4^{c}	2.59
Cysteine	75.9^{a}	69.4^{ab}	61.4^{bc}	59.7^{c}	3.34
Glutamic acid	83.8^{a}	81.6^{ab}	75.9^{c}	77.5^{bc}	2.14
Glycine	44.4^{a}	42.6^{a}	35.4^{ab}	26.2^{b}	4.56
Serine	77.7^{a}	75.3^{ab}	71.1^{b}	69.6^{b}	2.48
Tyrosine	77.8^{a}	71.6^{ab}	66.1^{b}	69.1^{b}	2.82
Total[3]	72.8^{a}	70.5^{a}	62.8^{b}	62.5^{b}	2.84
All AA	75.8^{a}	75.1^{a}	68.4^{b}	68.3^{b}	2.50

[1] Ten growing barrows (initially 25.9 kg) were fitted with a T-cannula in the distal ileum and were randomly allotted to one of five test diets in a 5-period design with 2 replicate pigs per diet in each period for a total of 10 replicates per pig diet.

[2] Total indispensable AA (IAA) = [1 − (total IAA in the digesta/total IAA in the diet) × (marker in the diet/marker in the digesta)] × 100.

[3] Total dispensable AA (DAA) = [1 − (total DAA in the digesta/total DAA in the diet) × (marker in the diet/marker in the digesta)] × 100.

[a–c] Values with different superscripts differ, $P < 0.05$.

[x,y] Values with different superscripts differ, $P < 0.10$.

with previous data (NRC, 2012; Li et al., 2014; Huang et al., 2017). Cereal grains have low concentrations of Ca compared with oil seed meals, and, therefore, inclusion of feed ingredients high in Ca or supplementation with limestone is necessary in diets for pigs. The analyzed values for total P in red sorghum and white sorghum are within the range of total P values for sorghum as reported by Selle et al. (2003) and Veum and Liu (2018), and the analyzed values for total P in high-lysine sorghum are in agreement with published values for high digestible sorghum (Nyannor et al., 2007). The observed differences among sorghum varieties may be attributed to differences in varieties and growing conditions (Veum and Liu, 2018).

Analyzed concentrations of indispensable AA and dispensable AA in corn, red sorghum, and white sorghum were in agreement with reported values (Sauvant et al., 2002; NRC, 2012; Cervantes-Pahm et al., 2014). When comparing the chemical analysis results for high-lysine sorghum used in these experiments to reported values for conventional sorghum in NRC (2012), differences were more obvious. Analyzed CP concentration was 13.9% in high-lysine sorghum compared with 9.36% in NRC (2012). On average, analyzed concentrations of indispensable AA were 56% greater in high-lysine sorghum compared with conventional sorghum (NRC, 2012). Specifically, Leu and Val concentrations were 2.08% and 0.71% in high-lysine sorghum compared with 1.21% and 0.46% in conventional sorghum (NRC, 2012). Differences between dispensable AA were larger than indispensable AA, with the average analyzed concentration of high-lysine sorghum being 108% greater than NRC (2012) conventional sorghum values. This was expected, as this is a new variety of sorghum selected for higher AA concentrations compared with conventional sorghum varieties.

Chemical analysis results indicate high-lysine sorghum having increased concentrations of all AA, except Lys, compared with the other varieties of conventional sorghum and corn. The observations agree with Goodband et al. (2016) who reported that the concentration of AA, specifically Thr, Trp, and Val, is greater in all varieties of sorghum compared with corn. The analyzed Lys concentration in high-lysine sorghum was greater compared with conventional sorghum varieties, but less compared with corn (0.26% vs. 0.28%). This was surprising; as the previous year, this specific variety of sorghum had an analyzed Lys concentration of 0.33%, compared with 0.26% in the present study, and 0.20% in the NRC (2012) for conventional sorghum. Thus, this variety of sorghum was named high-lysine based on the previous year's lysine concentration. It is likely that environmental and climatic differences will result in some variability from year to year in nutrient composition in sorghum. This has also been reported for other agricultural crops (Mathew et al., 1999; Sotak-Peper et al., 2016).

Nutritional value of grain sources

The STTD of P in corn without phytase observed in this experiment was slightly greater than values from previous experiments (Almeida and Stein, 2010, 2012; NRC, 2012; Rojas et al., 2013), which may be because of reduced phytate bound P in the corn used in this experiment. The mean STTD of P in all sorghum varieties without phytase was 41.5%, which is in agreement with previous data (Almeida et al., 2017). The addition of microbial phytase increased the ATTD and STTD

Table 11. SID of AA in yellow dent corn and different varieties of sorghum[1]

		Sorghum varieties			
Item	Corn	High-lysine	Red	White	SEM
Crude protein, %	92.8^{a}	84.5^{b}	81.5^{b}	81.9^{b}	2.48
Indispensable AA, %					
Arginine	91.8^{x}	87.0^{x}	85.2^{y}	85.4^{y}	1.90
Histidine	88.2^{a}	80.4^{b}	73.1^{c}	75.0^{bc}	3.05
Isoleucine	87.5^{a}	81.6^{ab}	77.9^{b}	78.5^{b}	2.60
Leucine	89.7^{a}	83.9^{b}	79.7^{b}	82.0^{b}	2.35
Lysine	82.7^{a}	70.2^{b}	67.9^{b}	72.1^{b}	3.72
Methionine	90.4^{a}	82.2^{b}	80.1^{b}	81.4^{b}	2.15
Phenylalanine	89.5^{a}	82.7^{b}	79.5^{b}	81.2^{b}	2.51
Threonine	86.4^{a}	76.7^{b}	74.9^{b}	74.6^{b}	3.87
Tryptophan	84.6	82.7	85.1	83.5	2.94
Valine	87.2^{a}	79.6^{b}	76.0^{b}	77.0^{b}	2.93
Total[2]	88.9^{a}	84.2^{ab}	80.8^{b}	81.9^{b}	2.24
Dispensable AA, %					
Alanine	91.4^{a}	83.7^{b}	80.2^{b}	82.3^{b}	2.28
Aspartic acid	89.9^{a}	81.2^{b}	79.5^{b}	79.0^{b}	2.59
Cysteine	86.4^{a}	77.2^{b}	71.3^{b}	71.8^{b}	3.34
Glutamic acid	83.8^{a}	81.6^{b}	75.9^{b}	77.5^{b}	2.14
Glycine	87.1	79.2	78.2	74.1	4.56
Serine	91.6^{a}	84.2^{b}	82.8^{b}	83.2^{b}	2.48
Tyrosine	87.8^{a}	77.6^{b}	74.5^{b}	77.9^{b}	2.82
Total[3]	88.2^{a}	78.7^{b}	74.9^{b}	76.2^{b}	2.84
All AA	88.6^{a}	81.8^{b}	78.1^{b}	79.3^{b}	2.50

[1] Ten growing barrows (initially 25.9 kg) were fitted with a T-cannula in the distal ileum and were randomly allotted to one of five test diets in a 5-period design with 2 replicate pigs per diet in each period for a total of 10 replicates per pig diet.

[2] Total indispensable AA (IAA) = [1 – (total IAA in the digesta/total IAA in the diet) × (marker in the diet/marker in the digesta)] × 100.

[3] Total dispensable AA (DAA) = [1 – (total DAA in the digesta/total DAA in the diet) × (marker in the diet/marker in the digesta)] × 100.

$^{a-c}$Values with different superscripts differ, $P < 0.05$.

^{x,y}Values with different superscripts x, y differ, $P < 0.10$.

of P in all ingredients, which indicate that exogenous phytase hydrolyzed some of the ester bonds between P and the inositol ring of phytate which resulted in increased absorption of P (Adeola et al., 1995).

In exp. 1, all diets contained 0.80% limestone, and because of the very low concentration of Ca in sorghum and in corn, the ATTD of Ca in the diets primarily reflects the ATTD of Ca in limestone. The mean ATTD of Ca in all sorghum varieties without phytase was 61.0%, and this value was not different from the ATTD of Ca in corn, which may indicate that similar proportions of Ca became bound to the phytate complex in the liquid environment of the stomach and small intestine. Addition of microbial phytase improved Ca digestibility in all four cereal grains used in this experiment, indicating an increase in Ca absorption by hydrolyzing the Ca–phytate complexes in the gut (Selle et al., 2009). This observation concurs with data demonstrating that ATTD and STTD of Ca in calcium carbonate increase as microbial phytase is added to diets (González-Vega et al., 2015; Lee et al., 2019).

In exp. 2, the DE and ME values for corn are in close agreement with previous data (Sauvant et al., 2004; NRC, 2012; Espinosa and Stein, 2018). Likewise, DE and ME of the three sorghum varieties were close to published values (Pan et al., 2016, 2017). The observation that white sorghum had a greater concentration of DE and ME compared with red sorghum is possibly a result of greater concentration of AEE in white sorghum compared with red sorghum. White sorghum belongs to type I sorghums that do not have pigmented testa and have a low concentration of tannin, whereas red sorghum is a type III sorghum variety, which has a greater concentration of tannin in both testa and pericarp (Ramachandra et al., 1977; Dykes and Rooney, 2006). The observation that DE and ME values in high-lysine sorghum were not different from DE and ME in corn and were greater compared with red sorghum is most likely a result of greater concentrations of CP and GE in high-lysine sorghum compared with the other cereal grains. Nevertheless, these data indicate that both high-lysine sorghum and white sorghum will provide the same quantities of ME to diets as corn.

In exp. 3, the AID values of CP for corn, red sorghum, and white sorghum were in agreement with values reported by NRC (2012). The AID of CP for high-lysine sorghum was greater (11.3%) than conventional sorghum reported by NRC (2012). On average, the AID values of the indispensable AA for corn and high-lysine sorghum were 3.6% and 8.1% greater than values reported in the NRC (2012). The AID values of indispensable AA for red sorghum and white sorghum were in agreement with values reported in the NRC (2012). Similarly, the AID values of dispensable AA of corn and high-lysine sorghum were 6.8% and 18.3% greater than values reported in the NRC (2012). The average AID of dispensable AA for red and white sorghum was 7.4% greater than the values reported by NRC (2012). These results are consistent with previous data indicating that AID values for most indispensable and dispensable AA for red and white sorghum varieties are lower than AID values in corn (Lin et al., 1987; Mariscal-Landín et al., 2010; Pan et al., 2017). The AID values for high-lysine sorghum were intermediate between corn and the conventional varieties of sorghum, with the exception of tryptophan. When expressing AA digestibility on the basis of AID, our results indicate the nutritional value of high-lysine sorghum being greater than that of conventional sorghum

Table 12. Growth performance, diarrhea score, and frequency of diarrhea of pigs fed diets containing high-lysine sorghum, red sorghum, white sorghum, or yellow dent corn, exp. 4[1,2]

		Sorghum varieties				
Item	Corn	High-lysine	Red	White	SEM	Probability, P-value <
BW, kg						
Day 0	6.3	6.3	6.3	6.3	0.56	0.516
Day 11	7.3	7.4	7.0	7.2	0.65	0.312
Day 20	10.5	10.8	10.1	10.3	0.84	0.541
Day 0 to 11						
ADG, g	93	100	58	75	16	0.308
ADFI, g	170	168	140	148	12	0.159
G:F	0.549	0.594	0.414	0.510	0.101	0.522
Day 11 to 20						
ADG, g	352	374	348	345	25	0.623
ADFI, g	484	485	465	448	35	0.738
G:F	0.730	0.772	0.748	0.773	0.022	0.456
Day 0 to 20						
ADG, g	208	223	187	198	20	0.506
ADFI, g	304	305	280	288	24	0.622
G:F	0.687	0.731	0.663	0.683	0.026	0.274
Diarrhea score[3]						
Day 0 to 11	2.29	2.17	2.06	2.19	0.127	0.598
Day 11 to 20	2.31	2.16	2.25	2.53	0.191	0.563
Day 0 to 20	2.30	2.16	2.14	2.33	0.104	0.489
Frequency of diarrhea						
Day 0 to 11						
Pen days[4]	48	48	48	48	—	—
Frequency[5]	43.75	41.67	37.50	43.75	—	0.916
Day 11 to 20						
Pen days[4]	32	32	32	32	—	—
Frequency[5]	43.75	34.38	40.63	53.13	—	0.495
Day 0 to 20						
Pen days[4]	80	80	80	80	—	—
Frequency[5]	43.75	38.75	38.75	47.50	—	0.619

[1] A total of 160 weaned pigs (initially 6.3 kg; Line 359 × Camborough; PIC, Hendersonville, TN) were randomly allotted to four dietary treatments with five pigs per pen and eight replicate pens per treatment.

[2] Data are least squares means of eight observations for all treatments.

[3] Diarrhea score = 1, normal feces; 2, moist feces; 3, mild diarrhea; 4, severe diarrhea; 5, watery diarrhea.

[4] Pen days = number of pens × the number of days assessing diarrhea scores.

[5] Frequency = (number of pen days with diarrhea scores ≥ 3/pen days) * 100.

varieties and comparable to corn. However, when accounting for endogenous losses and expressing AA digestibility as SID, the three varieties of sorghum appear to be similar.

In exp. 3, the SID values for most indispensable and dispensable AA for corn were greater than those for high-lysine, red, and white sorghum varieties, which is consistent with previous data (Pedersen et al., 2007; Cervantes-Pahm et al., 2014; Stein et al., 2016; Pan et al., 2017). This was expected because sorghum has lower digestibility of protein and AA compared with corn (Stein et al., 2016) caused by many factors, including tannins (Mariscal-Landin et al., 2010; Liu et al., 2013), polyphenols (Liu et al., 2016), kafirin (Liu et al., 2013), phytate (Selle et al., 2003; Stein et al., 2016), and fiber (Jaworski et al., 2015).

The low SID AA values observed in pigs consuming high-lysine, red, or white sorghum compared with pigs consuming corn indicates that when corn is replaced by different varieties of sorghum, more protein or AA supplementation is required to meet AA requirements. Cervantes-Pahm et al. (2014) also reported reduced SID of AA in sorghum compared with corn.

Nursery pig growth performance

In exp. 4, the observation that all parameters for growth performance were not different among pigs fed diets containing high-lysine sorghum, red sorghum, white sorghum, or corn indicates that sorghum varieties compare favorably with corn and can partially or fully replace corn in diet formulations. Similarly, the results from exp. 5 demonstrate that similar growth performance can be achieved in nursery pigs fed either corn or conventional sorghum. These observations agree with Goodband et al. (2016) who summarized 12 nursery studies comparing the growth performance of pigs fed sorghum diets to that of pigs fed corn-based diets and reported that the average relative value of sorghum was 99%, 100%, and 99% of the value of corn for ADG, ADFI, and G:F, respectively. The overall performance from exp. 5 indicates that the relative value of conventional sorghum (a blend of red and white) is 99%, 99%, and 100% of the value of corn for ADG, ADFI, and G:F, respectively. Similarly, the average overall performance for diets containing high-lysine sorghum indicates that the relative value of this specific variety of sorghum is 101%, 102%, and 99% of the value of corn

Table 13. Chemical analysis and AA analysis of experimental diets fed to nursery pigs (as-fed basis)[1]

			Feed-grade AA levels in high lysine sorghum diets			
Analyzed composition, %	Corn	Sorghum	Low	Low-Med	Med-High	High
Dry matter	89.1	89.6	90.4	90.3	89.9	90.4
Crude protein	21.6	22.5	23.9	24.0	22.4	21.0
Calcium	0.84	0.87	0.91	0.80	0.92	0.73
Phosphorus	0.59	0.62	0.65	0.64	0.70	0.63
Ether extract	4.3	4.4	4.9	4.7	4.2	w3.9
Ash	4.7	5.4	5.4	5.2	4.8	4.2
Indispensable AA, %						
Arginine	1.38	1.28	1.40	1.34	1.27	1.02
Histidine	0.55	0.52	0.58	0.56	0.54	0.47
Isoleucine	0.94	0.96	1.10	1.06	1.01	0.89
Leucine	1.82	1.87	2.32	2.33	2.27	2.18
Lysine	1.42	1.37	1.40	1.36	1.47	1.41
Methionine	0.44	0.44	0.45	0.47	0.45	0.45
Phenylalanine	1.07	1.07	1.26	1.22	1.18	1.06
Threonine	0.91	0.86	0.88	0.87	0.91	0.83
Tryptophan	0.28	0.28	0.28	0.28	0.28	0.25
Valine	1.06	1.04	1.18	1.14	1.08	1.05
Dispensable AA, %						
Alanine	1.05	1.14	1.40	1.43	1.39	1.36
Aspartic acid	2.09	2.04	2.29	2.18	2.09	1.73
Cysteine	0.37	0.34	0.38	0.37	0.37	0.32
Glutamic acid	3.69	3.68	4.43	4.37	4.20	3.83
Glycine	0.87	0.82	0.89	0.85	0.81	0.68
Serine	0.92	0.87	0.99	0.97	0.94	0.81
Tyrosine	0.76	0.75	0.87	0.85	0.82	0.71
All AA	19.59	19.29	22.06	21.61	21.14	19.00

[1] Complete diet samples were taken from five feeders per dietary treatment three times throughout the study. Samples were stored at −20 °C until they were homogenized, subsamples, and submitted to Ward Laboratories, Inc. (Kearney, NE) for proximate analysis and the University of Missouri Agricultural Experiment Station Chemical Laboratory (Columbia, MO) for AA analysis performed in duplicate. Reported values are an average of duplicate analysis.

Table 14. Effect of high-lysine sorghum on nursery pig growth performance[1]

			Feed-grade AA levels in high-lysine sorghum diets					Probability, *P*-value <		
Item	Corn	Sorghum	Low	Low-Med	Med-High	High	SEM	Treatment	Linear[2]	Quadratic[3]
BW, kg										
Day 0	9.6	9.7	9.7	9.6	9.7	9.6	0.20	1.000	0.946	0.942
Day 20	20.9	20.8	21.3	20.9	21.0	20.7	0.33	0.418	0.096	0.868
Day 0 to 20										
ADG, g	560	557	582	565	569	555	9.54	0.262	0.055	0.831
ADFI, g	858	851	881	856	872	898	17.9	0.361	0.259	0.258
G:F	0.654	0.656	0.661	0.662	0.655	0.618	0.0106	0.045	0.003	0.194

[1] A total of 293 pigs (DNA Line 241 × 600; initially 9.7 kg) were used in a 20-d experiment with five pigs per pen and 10 replications per treatment.

[2,3] Linear and quadratic effects of increasing high-lysine sorghum.

for ADG, ADFI, and G:F, respectively. Pan et al. (2017) evaluated the growth performance in weaned pigs fed diets containing either 60% corn, 40% corn and 20% sorghum, 20% corn and 40% sorghum, or 60% sorghum and reported no differences in ADG or ADFI, but found a reduction in G:F in pigs consuming sorghum. Differences in the G:F response could be the causes of different varieties of sorghum or formulation methods. However, the energy content of sorghum is believed to be 98% to 99% relative to that of corn due to a reduction in oil concentration (Jaworski et al., 2015) which can result in a reduction in G:F in pigs fed sorghum-based diets compared with those fed corn-based diets (Menegat et al., 2019). However, G:F can be improved by grinding sorghum-based diets to a finer particle size (Owsley et al., 1981; Paulk et al., 2015).

In exp. 5, in addition to comparing the relative feeding value of different varieties of sorghum to that of corn, the experiment was designed to evaluate the partial replacement of SBM in the diet with a specific variety of high-lysine sorghum. By using feed-grade AA, diets were balanced appropriately as the amount of SBM decreased. Results indicated that as inclusion of high-lysine sorghum and feed-grade AA in the diet increased, nursery pig ADG and G:F were negatively affected. We speculate that dispensable AA may have become limiting as the amount of SBM in the diet decreased, resulting in a reduction in dietary CP.

A ratio of 6.35 g SID Lys/g CP has been suggested as a threshold value, and dispensable AA may limit the growth performance of pigs if the ratio is lower than that (Millet et al., 2018). In this experiment, diets formulated with high-lysine sorghum with the med-high and high-feed-grade AA had calculated SID Lys:CP ratios exceeding the threshold value, at 6.4 and 7.2 g SID Ly/g CP.

Implications

In conclusion, 1) the ATTD and STTD of P of high-lysine sorghum were not different from values obtained for conventional varieties of sorghum or corn when fed to growing pigs; 2) addition of microbial phytase improves the STTD of P in all ingredients, and if 500 FTU of phytase is added to sorghum, the STTD of P is between 60% and 67%; 3) the concentrations of DE and ME in high-lysine sorghum, as well as growth performance of pigs when fed diets based on high-lysine sorghum, were not different from data obtained for corn; 4) there was no evidence that the SID AA values for the high-lysine sorghum variety used in this study were different from the red or white sorghum varieties; 5) regardless of the variety of sorghum, corn had the greatest SID AA digestibility coefficient values; and 6) pigs fed corn-, conventional sorghum-, or high-lysine sorghum-based diets formulated on an SID AA basis have similar growth performance.

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Conflict of interest statement

The authors declare no real or perceived conflicts of interest.

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