

# Concentration of digestible and metabolizable energy, standardized ileal digestibility, and growth performance of pigs fed diets containing sorghum produced in the United States or corn produced in China<sup>1</sup>

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**ABSTRACT:** The DE and ME content (Exp. 1) as well as the apparent ileal digestibility (AID) and standardized ileal digestibility (SID) of essential AA (EAA; Exp. 2) were compared between Chinese corn and U.S. sorghum. The effects of U.S. sorghum as a potential substitute for Chinese corn on growth performance of 114 weaned pigs ( $8.8 \pm 1.0$  kg BW; Exp. 3) and 60 growing pigs ( $23.4 \pm 1.6$  kg BW; Exp. 4) were evaluated, and the effect of protease supplementation on N utilization was determined in sorghum-based diets fed to growing pigs (Exp. 4). In Exp. 1, there was no difference in DE and ME content between corn and sorghum. In Exp. 2, the AID and SID of most EAA and the concentrations of standardized ileal digestible Lys, Met, Thr, and His were less in sorghum than in corn ( $P < 0.05$ ). In Exp. 3, there was no difference in ADG and ADFI among treatments during the experimental period. The G:F and apparent total tract digestibility (ATTD) of CP was decreased for pigs fed diets with sorghum in the first 2 wk ( $P < 0.05$ ) and for pigs fed diets containing 60% sorghum in the following 2 wk ( $P < 0.05$ ). The fecal score for pigs fed diets

with sorghum, regardless of the substitute level, was less ( $P < 0.05$ ) or tended to be less ( $P = 0.086$ ) than that for pigs fed diets containing 60% corn. In Exp. 4, no differences were observed in ADG and ADFI overall among pigs fed diets based on corn and soybean meal (CSBM) or sorghum and soybean meal (SSBM). Pigs fed CSBM or SSBM with protease supplementation had greater ( $P < 0.05$ ) or tended to have greater ( $P = 0.062$ ) G:F than pigs fed SSBM. Compared with CSBM, SSBM increased fecal N excretion by more than 25% and decreased the ATTD of CP by more than 7% during the whole experiment ( $P < 0.05$ ). Protease supplementation reduced fecal N excretion by more than 12% and increased ATTD of CP by more than 6% ( $P < 0.05$ ). In conclusion, based on optimal G:F and CP digestibility, diets for weaned pigs should contain less than 20% sorghum during the first 2 wk and no more than 40% during the subsequent 2 wk after weaning. Sorghum used as an alternative energy source for corn in diets fed to growing pigs decreases CP utilization by increasing manure N output, which might be partially offset by protease supplementation.

**Key words:** energy, growth performance, nitrogen, pigs, protease, sorghum

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## INTRODUCTION

Sorghum contains a unique structure of protein bodies, which compromises N and energy utilization by physical and chemical interactions (Salinas et al., 2006;

Liu et al., 2013a,c), but this could be addressed, at least partially, by exogenous protease for broilers (Xu et al., 2017) and pigs (Pan et al., 2017). Sorghum is not always comparable to corn, mainly due to its relatively high tannin content (Khoddami et al., 2015; Pan et al., 2016a). Accordingly, once favorably priced, low-tannin sorghum is usually used as an alternative energy source to reduce diet cost and an overdependence on corn (Yin et al., 2002; Paulk et al., 2015; Xie et al., 2017).

As is well known, the United States is the largest producer and exporter of sorghum grain, accounting for almost 20% of world production and 80% of

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world sorghum exports in 2016 and 2017 (USDA-FAS, 2017). It has been reported that more than 99% of U.S. sorghum is tannin free due to decades of breeding efforts, and the nontannin sorghum grown for livestock feed has virtually the same energy profile as corn (Awika and Rooney, 2004). Unfortunately, the majority of Chinese-produced sorghum grain is used to produce liquor and vinegar for these cultivars possessing high tannin content required for liquor and vinegar flavor, and only a very small proportion is used for human food or feed (Diao, 2017). With the price of corn soaring in recent years, China has imported large amounts of U.S. sorghum as animal feed (Diao, 2017). However, there is a dearth of studies to accurately evaluate the nutritional value of U.S. sorghum grain.

We hypothesized that sorghum imported from the United States has a similar energy content but low N utilization compared with corn produced in China and that the increased manure N output from growing pigs fed a sorghum-based diet could be offset by protease supplementation. Therefore, the objectives of 4 experiments were to compare DE and ME content (Exp. 1) as well as apparent ileal digestibility (AID) and standardized ileal digestibility (SID) of essential AA (EAA) and standardized ileal digestible EAA composition (Exp. 2) between Chinese corn and U.S. sorghum, to evaluate effects of U.S. sorghum as a potential substitute for Chinese corn on growth performance and apparent total tract digestibility (ATTD) of nutrients in weaned (Exp. 3) and growing pigs (Exp. 4), and to determine whether protease could improve CP utilization by reducing manure N output in a sorghum-based diet fed to growing pigs (Exp. 4).

## MATERIALS AND METHODS

The experimental protocols used in these experiments, including animal care and use, were approved by the Institutional Animal Care and Use Committee of China Agricultural University (Beijing, P.R. China).

### General

These studies were conducted in the Swine Nutrition Research Center of the National Feed Engineering Technology Research Center (Chengde, P.R. China) for Exp. 1, 3, and 4 and in the Metabolism Laboratory of the Ministry of Agriculture Feed Industry Centre (China Agricultural University, Beijing, P.R. China) for Exp. 2.

Yellow dent corn (*Zea mays* L.) produced in China was obtained from the Swine Nutrition Research Center of the National Feed Engineering Technology Research Center. The sorghum (*Sorghum bicolor*) sample imported from the United States was purchased from the Tianjin Fujiadesenhe International Trading Company in

Tianjin (P.R. China). Both grains were ground in a hammer mill using a 2-mm screen. The analyzed chemical composition of the corn and sorghum grain is presented in Table 1. The protease with activity of 10,000 units/g used in Exp. 4 is extracted from the porcine pancreas and small intestines and provided by Shanghai Honest Biological Technology Company (Shanghai, P.R. China).

All diets in these experiments were fed in mash form, and the experimental pigs (Duroc × Landrace × Yorkshire) were provided by the Swine Nutrition Research Centre of the National Feed Engineering Technology Research Centre.

### Experimental Design and Sample Collection

**Experiment 1: Energy Measurement.** The objective of this experiment was to determine DE and ME as well as ATTD of GE of corn and sorghum grain. Twelve barrows ( $36.7 \pm 2.0$  kg BW) were randomly allotted to 1 of 2 diets with 6 barrows per treatment. The diets were formulated to contain 96.9% of corn or sorghum grain and 3.1% of vitamins and minerals (Table 2).

All pigs were individually housed in stainless-steel metabolism crates (1.4 by 0.7 by 0.6 m) equipped with a feeder and a nipple drinker located in an environmentally controlled room with the temperature maintained at  $22 \pm 2^\circ\text{C}$ . Barrows were provided ad libitum access to water and were fed an amount of feed each day equivalent to 4% of their BW determined at the beginning of the experiment. The daily feed was divided into 2 equal sized portions and provided at 0800 and 1600 h, and the amount of feed provided was recorded at each feeding time.

The experiment lasted 12 d, including 7 d for adaptation to the diets and 5 d for the collection of feces and urine. During the collection period, feed refusals and spillage were collected twice daily and subsequently dried and weighed. Feces were collected from each pig as soon as they appeared in the metabolism crates and were immediately stored in plastic bags at  $-20^\circ\text{C}$ . Urine was collected in buckets, containing 50 mL of 6 N HCl, located under the metabolism crates (Pan et al., 2016c). The volume of collected urine was measured each day, and 10% of the daily urinary collection was stored at  $-20^\circ\text{C}$ . At the end of collection, feces and urine were separately thawed, pooled by pig, homogenized, and subsampled. Before chemical analysis, fecal subsamples were dried at  $65^\circ\text{C}$  in a drying oven for 72 h. Urine samples (4 mL) were dried at  $65^\circ\text{C}$  for 8 h with quantitative filter paper in crucibles (Li et al., 2015).

**Experiment 2: Amino Acid Digestibility.** This experiment was conducted to determine the AID and SID of CP and EAA and the standardized ileal digestible EAA composition in corn and sorghum. The experiment was

**Table 1.** Analyzed chemical composition of corn and sorghum (% , as-fed basis)<sup>1</sup>

Item	Corn	Sorghum
DM	88.25	87.63
GE, MJ/kg	16.28	16.10
CP	7.94	7.98
Prolamin	4.29	5.91
Ether extract	2.34	1.82
Ash	1.22	1.33
NDF	15.05	10.50
ADF	3.30	3.05
Starch	61.46	67.48
Ca	0.04	0.02
Total P	0.23	0.26
Phytate	0.37	0.70
Tannin	0.01	0.05
Total phenols	0.12	0.34
Indispensable AA		
Lys	0.23	0.21
Met	0.18	0.16
Thr	0.29	0.30
Trp	0.06	0.07
Val	0.40	0.45
Leu	1.04	1.01
Ile	0.25	0.33
Phe	0.36	0.39
His	0.23	0.20
Arg	0.31	0.34
Dispensable AA		
Tyr	0.19	0.17
Ser	0.35	0.33
Glu	1.32	1.60
Pro	0.65	0.68
Gly	0.30	0.27
Ala	0.55	0.65
Cys	0.25	0.22
Asp	0.49	0.50
Total indispensable AA	3.73	3.46
Total dispensable AA	4.10	4.42
Total AA	7.45	7.88

<sup>1</sup>All values are the results of an analysis conducted in duplicate.

conducted using 18 crossbred barrows ( $24.9 \pm 1.4$  kg BW) fitted with T-cannulas at the terminal ileum according to the method of Stein et al. (1998). The barrows were individually housed in stainless-steel metabolism crates (1.4 by 0.7 by 0.6 m) located in a temperature-controlled room ( $22 \pm 2^\circ\text{C}$ ) and were fed 1 of 3 diets, with 6 barrows per diet, in a completely randomized design.

The N-free diet, containing 73.5% cornstarch and 15% sucrose, was used to determine basal ileal endogenous N losses (Chen et al., 2016), and the other 2 diets contained 96.6% corn or sorghum as the only source of dietary N (Table 2). Chromic oxide (0.3%) was included in all diets as an indigestible marker. Vitamins and minerals were supplemented in all diets

**Table 2.** Composition of experimental diets in Exp. 1 and 2 (% , as-fed basis)

Item	Exp. 1		Exp. 2		
	Corn diet	Sorghum diet	Corn diet	Sorghum diet	N-free diet
Ingredient					
Corn	96.9	–	96.6	–	–
Sorghum	–	96.9	–	96.6	–
Corn starch	–	–	–	–	73.5
Sucrose	–	–	–	–	15.0
Cellulose acetate	–	–	–	–	4.0
Soybean oil	–	–	–	–	3.0
Dicalcium phosphate	1.7	1.7	1.7	1.7	2.5
Limestone	0.6	0.6	0.6	0.6	0.5
Sodium chloride	0.3	0.3	0.3	0.3	0.3
Chromic oxide	–	–	0.3	0.3	0.3
Potassium carbonate	–	–	–	–	0.3
Magnesium oxide	–	–	–	–	0.1
Vitamin and mineral premix <sup>1</sup>	0.5	0.5	0.5	0.5	0.5
Analyzed nutrient level					
DM	89.68	89.20	89.88	89.38	90.80
CP	7.68	7.76	7.69	7.75	0.48
Ash	3.60	3.62	3.77	3.81	5.02
Ca	0.68	0.65	0.68	0.65	0.78
Total P	0.55	0.57	0.55	0.57	0.54
Indispensable AA					
Lys			0.23	0.20	0.01
Met			0.17	0.16	–
Thr			0.25	0.26	0.01
Trp			0.06	0.07	–
Val			0.41	0.47	0.01
Leu			1.00	0.98	0.02
Ile			0.24	0.32	0.01
Phe			0.34	0.37	0.02
His			0.21	0.18	0.01
Arg			0.32	0.35	0.01
Dispensable AA					
Tyr			0.20	0.18	0.01
Ser			0.34	0.31	0.02
Glu			1.30	1.58	0.04
Pro			0.63	0.64	0.01
Gly			0.31	0.28	0.02
Ala			0.55	0.65	0.02
Cys			0.22	0.21	0.01
Asp			0.48	0.50	0.02

<sup>1</sup>Vitamin and mineral premix provided the following per kilogram of diet: 12,000 IU vitamin A as vitamin A acetate, 2,500 IU vitamin D as vitamin D<sub>3</sub>, 30 IU vitamin E as DL- $\alpha$ -tocopheryl acetate, 12  $\mu\text{g}$  vitamin B<sub>12</sub>, 3 mg vitamin K as menadione sodium bisulfate, 15 mg d-pantothenic acid as calcium pantothenate, 40 mg nicotinic acid, 400 mg choline as choline chloride, 30 mg Mn as manganese oxide, 80 mg Zn as zinc oxide, 90 mg Fe as iron sulfate, 10 mg Cu as copper sulfate, 0.35 mg I as ethylenediamine dihydroiodide, and 0.3 mg Se as sodium selenite.

to meet or exceed the estimated nutrient requirements for growing pigs (NRC, 2012). All pigs were fed at a daily level of 4% of BW. Two equal-sized meals were provided at 0800 and 1700 h each day.

After a full recovery period, the barrows were fed 1 of 3 diets for a 7-d period, consisting of a 5-d dietary acclimation period followed by a 2-d digesta collection, which lasted for 9 h daily beginning at 0800 h using the procedures described by Stein et al. (1998). On d 6 and 7, a plastic bag was attached to the barrel of the cannula. The bags were removed whenever they were filled with digesta or at least every 30 min and then stored at  $-20^{\circ}\text{C}$  to prevent bacterial degradation of AA in the digesta (Pan et al., 2016b). At the end of the experiment, digesta samples were thawed, mixed by pig and period, subsampled, and lyophilized in a vacuum freeze-dryer (Tofflon Freezing Drying Systems, Minhang District, Shanghai, P.R. China).

**Experiment 3: Growth Performance and Fecal Score of Weaned Pigs.** This study evaluated the effects and optimum substitution level of the U.S. sorghum as a potential replacement for corn on growth performance, ATTD of nutrients, and fecal score in weaned pigs. A total of 144 healthy weaned pigs ( $8.8 \pm 1.0$  kg BW and  $28 \pm 3$  d of age) were assigned to 4 treatments according to sex and weight in a randomized complete block design. Each treatment diet was fed to 6 replicate pens, with 6 pigs (3 barrows and 3 gilts) per pen.

The energy sources of 4 diets were mainly 60% corn, 40% corn and 20% sorghum, 20% corn and 40% sorghum, or 60% sorghum (Table 3). Extra EAA were incorporated into the diets based on the standardized ileal digestible EAA concentration derived from Exp. 2. All diets, with 0.25% chromic oxide added as an indigestible marker (Wu et al., 2017), were formulated to meet the nutrient requirements for pigs according to the NRC (2012).

Pigs were housed in pens with fully slatted floors, and all pigs had free access to feed and water throughout the 28-d experiment. The temperature of the barn was controlled between 23 and  $28^{\circ}\text{C}$ , and relative humidity was controlled at 60 to 70%. Pigs and feed were weighed at the beginning (d 1), mid stage (d 14), and end (d 28) to determine ADG, ADFI, and G:F. Piglets were observed for clinical signs of diarrhea every day (Pan et al., 2016b), and a scoring system was applied to indicate the presence and severity of diarrhea as following: 1 = hard feces; 2 = slightly soft feces; 3 = soft, partially formed feces; 4 = loose, semiliquid feces; and 5 = watery, mucous-like feces. From d 11 to 13 and from d 25 to 27, approximately 100 g of feces was collected from each pen for 3 d, and the fecal samples were stored at  $-20^{\circ}\text{C}$  prior to being oven dried (Pan et al., 2017c). The 3-d collection of feces was pooled by pen and then dried at  $65^{\circ}\text{C}$  for 72 h.

**Experiment 4: Effects of Protease on N Utilization.** This study was conducted to determine effects of sorghum as a replacement for corn on growth performance in growing pigs and effects of protease on N utilization for growing pigs fed sorghum-based diets. Sixty growing pigs ( $23.4 \pm 1.6$  kg BW) were allotted to 3 diets with 5 replicate pens per treatment (2 barrows and 2 gilts per pen) according to sex and weight in a randomized complete block design.

The experiment lasted for 70 d, including phase 1 (d 1 to 35) and phase 2 (d 36 to 70). The 3 diets were based on corn and soybean meal (CSBM) or sorghum and soybean meal (SSBM) without or with 150 mg/kg protease supplementation ( $1.5 \pm 0.4$  units/g of diet). The energy sources of CSBM or SSBM mainly included 70.34% corn or 20% corn and 50% sorghum in phase 1 and 73.6% corn or 73.4% sorghum in phase 2 (Table 4). All diets, with 0.25% chromic oxide added as an indigestible marker, were formulated to meet or exceed the nutrient requirements for growing pigs (25 to 50 kg and 50 to 75 kg) according to the NRC (2012).

During the experiment, pigs were housed in partially steel-slatted and concrete-floored pens (2.7 by 1.8 m). Each pen was equipped with a stainless steel self-feeder and a nipple drinker. Pigs had ad libitum access to diets and water. Pigs and feeders were weighed on d 1, 35, and 70 to calculate ADG, ADFI, and G:F. From d 32 to 34 and from d 67 to 69, approximately 200 g of feces was collected from each pen for 3 d, and the fecal samples were stored at  $-20^{\circ}\text{C}$  prior to being oven dried (Pan et al., 2017). The 3-d collection of feces was pooled by pen and then dried at  $65^{\circ}\text{C}$  for 72 h.

### Chemical Analysis and Calculations

All samples were ground to pass through a 1-mm screen and thoroughly mixed before analysis. All chemical analyses were conducted in duplicate. The chemical analyses of the ingredients, diets, and feces included DM (method 930.15; AOAC, 2006), CP (method 984.13; AOAC, 2006), ether extract (method 920.39; AOAC, 2006), ash (method 942.05; AOAC, 2006), Ca (method 968.08; AOAC, 2006), and P (method 946.06; AOAC, 2006). The NDF and ADF contents were determined using fiber bags (model F57; ANKOM Technology Corp., Macedon, NY) and a fiber analyzer (ANKOM200 Fiber Analyzer; ANKOM Technology Corp.) using the basic procedure of Van Soest et al. (1991) with heat-stable  $\alpha$ -amylase and sodium sulfite and expressed inclusive of residual ash (Pan et al., 2014). The GE of ingredients, diets, feces, and urine were measured using an Automatic Isoperibol Oxygen Bomb Calorimeter (Parr 6300 Calorimeter; Parr Instrument Company, Moline, IL). Total starch was measured using method 76-

**Table 3.** Ingredient and nutrient contents of diets in Exp. 3 (% , as-fed basis)

Item	d 1 to 14				d 15 to 28			
	Corn:sorghum ratio				Corn:sorghum ratio			
	60:0	40:20	20:40	0:60	60:0	40:20	20:40	0:60
<b>Ingredient</b>								
Corn	60.0	40.0	20.0	–	60.0	40.0	20.0	–
Sorghum	–	20.0	40.0	60.0	–	20.0	40.0	60.0
Soybean meal	9.61	9.57	9.52	9.48	15.25	15.22	15.20	15.15
Extruded soybean meal	12.0	12.0	12.0	12.0	12.0	12.0	12.0	12.0
Spray-dried porcine plasma	4.0	4.0	4.0	4.0	–	–	–	–
Fish meal	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Whey powder	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Soybean oil	2.9	2.9	2.9	2.9	1.6	1.6	1.6	1.6
Dicalcium phosphate	0.9	0.9	0.9	0.9	0.7	0.7	0.7	0.7
Limestone	1.0	1.0	1.0	1.0	0.8	0.8	0.8	0.8
Salt	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
L-Lys HCl	0.35	0.36	0.38	0.39	0.36	0.38	0.39	0.41
DL-Met	0.10	0.12	0.14	0.16	0.09	0.09	0.10	0.12
L-Thr	0.07	0.08	0.09	0.10	0.12	0.13	0.13	0.14
L-Trp	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03
Chromic oxide	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Vitamin mineral premix <sup>1</sup>	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
<b>Analyzed nutrient level</b>								
DM	89.8	89.9	89.7	90.2	89.4	89.7	89.7	89.9
CP	20.0	19.8	19.9	19.7	18.9	19.1	18.9	18.7
Ash	5.71	5.65	5.68	5.76	5.31	5.38	5.49	5.32
Ca	0.82	0.82	0.81	0.80	0.72	0.71	0.71	0.70
Total P	0.64	0.64	0.64	0.65	0.58	0.58	0.59	0.59
<b>Calculated nutrient level<sup>2</sup></b>								
Standardized ileal digestible Lys	1.35	1.35	1.35	1.35	1.23	1.23	1.23	1.23
Standardized ileal digestible Met	0.39	0.39	0.39	0.39	0.37	0.37	0.37	0.37
Standardized ileal digestible Thr	0.79	0.79	0.79	0.79	0.73	0.73	0.73	0.73
Standardized ileal digestible Trp	0.22	0.22	0.22	0.22	0.20	0.20	0.20	0.20
ME, Mcal/kg	3.40	3.40	3.40	3.40	3.35	3.35	3.35	3.35

<sup>1</sup>Vitamin and mineral premix provided the following per kilogram of diet: 12,000 IU vitamin A as vitamin A acetate, 2,500 IU vitamin D as vitamin D<sub>3</sub>, 30 IU vitamin E as DL- $\alpha$ -tocopheryl acetate, 12  $\mu$ g vitamin B<sub>12</sub>, 3 mg vitamin K as menadione sodium bisulfate, 15 mg d-pantothenic acid as calcium pantothenate, 40 mg nicotinic acid, 400 mg choline as choline chloride, 30 mg Mn as manganese oxide, 80 mg Zn as zinc oxide, 90 mg Fe as iron sulfate, 10 mg Cu as copper sulfate, 0.35 mg I as ethylenediamine dihydroiodide, and 0.3 mg Se as sodium selenite.

<sup>2</sup>These values were calculated from data provided in Exp. 1 and 2.

13.01 of the American Association of Cereal Chemists (1976), conducted using a commercial Starch Assay Kit (STA20; Sigma-Aldrich Corp., St. Louis, MO). The sorghum and corn grains were also analyzed for prolammin (Hamaker et al., 1995), tannin (Price et al., 1978), phytate (Skoglund et al., 1997a,b), and total phenols by the Folin–Ciocalteu method (Kaluza et al., 1980). Total phenols were calculated and expressed as grams gallic acid equivalent/100-g sample. Amino acid analysis in the lab was detailed by Pan et al. (2016b). The chromium content in the diets and feces was measured using an Atomic Absorption Spectrophotometer (Z-5000; Hitachi, Ltd., Tokyo, Japan) according to the procedure of Williams et al. (1962).

Calculations for DE and ME in corn and sorghum grains (Exp. 1) were detailed by Pan et al. (2016a). Gross

energy intake was calculated as the product of the GE content of the diet and the actual feed intake over the 5-d collection period. The energy lost in feces and urine was measured for each diet, and the DE and ME contents of the diets were calculated. The DE and ME contents in the diets were divided by 0.969 to calculate the DE and ME values in the corresponding ingredient samples. The ATTD of nutrients in each diet was calculated according to the procedures described by Adeola (2001):  $ATTD (\%) = 100\% \times (GE_i - GE_f)/GE_i$ , in which  $GE_i$  is the total GE intake of each pig (kcal of DM) calculated as the product of the GE of the diet over the actual feed intake during the 5-d collection period and  $GE_f$  is the GE content in feces of each pig (kcal of DM) calculated as the GE content of the feces over the dry weight of total feces obtained during the 5-d collection period.

**Table 4.** Ingredient and nutrient contents of diets in Exp. 4 (% , as-fed basis)<sup>1</sup>

Item	d 1 to 35			d 36 to 70		
	CSBM	SSBM		CSBM	SSBM	
		-	+		-	+
<b>Ingredient</b>						
Corn	70.34	20.0	20.0	73.6	-	-
Sorghum	-	50.0	50.0	-	73.4	73.4
Soybean meal	24.0	24.0	24.0	21.0	21.0	21.0
Wheat bran	2.00	2.00	2.00	2.00	2.00	2.00
Soybean oil	0.55	0.55	0.55	0.43	0.43	0.43
Dicalcium phosphate	0.86	1.00	1.00	0.65	0.90	0.90
Limestone	0.98	0.85	0.85	0.96	0.77	0.77
Sodium chloride	0.30	0.30	0.30	0.30	0.30	0.30
L-Lys HCl	0.31	0.34	0.34	0.23	0.28	0.28
DL-Met	0.06	0.10	0.10	0.03	0.09	0.09
L-Thr	0.08	0.10	0.10	0.04	0.07	0.07
L-Trp	0.02	0.01	0.01	0.01	0.01	0.01
Chromic oxide	0.25	0.25	0.25	0.25	0.25	0.25
Vitamin and mineral premix <sup>2</sup>	0.50	0.50	0.50	0.50	0.50	0.50
<b>Analyzed nutrient level</b>						
DM	88.7	88.9	89.0	88.7	89.1	89.0
CP	17.3	17.2	17.1	16.1	16.0	16.0
Ash	4.94	4.93	5.06	4.50	4.73	4.75
Ca	0.68	0.67	0.67	0.62	0.61	0.60
Total P	0.56	0.55	0.54	0.54	0.53	0.52
<b>Calculated nutrient level<sup>3</sup></b>						
Standardized ileal digestible Lys	0.98	0.98	0.98	0.85	0.85	0.85
Standardized ileal digestible Met	0.28	0.28	0.28	0.24	0.24	0.24
Standardized ileal digestible Thr	0.59	0.59	0.59	0.52	0.52	0.52
Standardized ileal digestible Trp	0.17	0.17	0.17	0.15	0.15	0.15
ME, Mcal/kg	3.30	3.30	3.30	3.30	3.30	3.30

<sup>1</sup>CSBM = corn and soybean meal; SSBM = sorghum and soybean meal; “-” = without protease; “+” = with 150 mg/kg protease supplementation (1.5 ± 0.4 units/g of diet).

<sup>2</sup>During d 1 through 35, the vitamin and mineral premix provided the following per kilogram of diet: 6,000 IU vitamin A as vitamin A acetate, 2,400 IU vitamin D as vitamin D<sub>3</sub>, 21.6 IU vitamin E as DL- $\alpha$ -tocopheryl acetate, 2 mg vitamin K as menadione sodium bisulfate, 0.96 mg vitamin B<sub>1</sub>, 5.2 mg vitamin B<sub>2</sub>, 2 mg vitamin B<sub>6</sub>, 12  $\mu$ g vitamin B<sub>12</sub>, 11.2 mg d-pantothenic acid as calcium pantothenate, 22 mg nicotinic acid, 400 mg choline as choline chloride, 0.4 mg folic acid, 40  $\mu$ g biotin, 120 mg Fe as iron sulfate, 130 mg Cu as copper sulfate, 20 mg Mn as manganese oxide, 0.4 mg I as ethylenediamine dihydroiodide, and 0.3 mg Se as sodium selenite. During d 36 through 70, the vitamin and mineral premix provided the following per kilogram of diet: 5,600 IU vitamin A as vitamin A acetate, 2,200 IU vitamin D as vitamin D<sub>3</sub>, 21.6 IU vitamin E as DL- $\alpha$ -tocopheryl acetate, 1.8 mg vitamin K as menadione sodium bisulfate, 0.88 mg vitamin B<sub>1</sub>, 4 mg vitamin B<sub>2</sub>, 1.8 mg vitamin B<sub>6</sub>, 12  $\mu$ g vitamin B<sub>12</sub>, 10 mg d-pantothenic acid as calcium pantothenate, 20 mg nicotinic acid, 320 mg choline as choline chloride, 0.4 mg folic acid, 40  $\mu$ g biotin, 100 mg Fe as iron sulfate, 15 mg Cu as copper sulfate, 10 mg Mn as manganese oxide, 0.3 mg I as ethylenediamine dihydroiodide, and 0.3 mg Se as sodium selenite.

<sup>3</sup>These values were calculated from data provided in Exp. 1 and 2.

The AID and SID of AA and CP (Exp. 2) were calculated as described by Stein et al. (2007) using the following equation: AID (%) = [1 - (AAd/AAf) × (Crf/Crd)] × 100%, in which AAd and Crd are the concentrations of AA and Cr, respectively, in the ileal digesta (g/kg of DM) and AAf and Crf are the concentrations of AA and Cr, respectively, in the test diets (g/kg of DM). The AID of CP was calculated using the equation shown above. The endogenous loss of N for each AA was measured from pigs fed the N-free diet based on the following equation: IAAend = [AAd × (Crf/Crd)], in which IAAend is the basal endogenous loss of an AA (g/kg of DM intake) and AAd and Crd represent the concen-

trations of AA and Cr, respectively, in the ileal digesta from the pigs fed the N-free diet. The Cr concentration in the N-free diet is represented by Crf. The endogenous loss of CP was determined using the same equation. The average IAAend for the 6 pigs fed the N-free diet was used to calculate the SID of AA in all diets. The SID value was calculated using the following equation: SID (%) = [AID + (IAAend/AAf) × 100%]. The SID value of each AA was multiplied by the concentration of AA (DM basis) to calculate the concentration of standardized ileal digestible AA (Pan et al., 2016c).

The ATTD of nutrients (Exp. 3 and 4) and estimated manure N output (Exp. 4) were calculated as de-

**Table 5.** Concentration of DE and ME content (MJ/kg, DM basis) and apparent total tract digestibility (ATTD) of nutrients (%) in corn and sorghum grains (Exp. 1)<sup>1</sup>

Item	Corn	Sorghum	SEM	<i>P</i> -value
DE	16.36	16.35	0.06	0.95
ME	16.10	16.09	0.04	0.99
ATTD of OM	90.28	91.20	0.36	0.12
ATTD of GE	87.90	88.06	0.30	0.71
ATTD of CP	77.79	73.72	1.01	0.04

<sup>1</sup>Values are the means of 6 observations per grain.

scribed by Pan et al. (2017). Nutrient digestibility was determined by the equation as follows: ATTD of nutrient (%) =  $[1 - (Cr_{\text{diet}} \times \text{nutrient}_{\text{feces}}) / (Cr_{\text{feces}} \times \text{nutrient}_{\text{diet}})] \times 100\%$ , in which,  $Cr_{\text{diet}}$  or  $Cr_{\text{feces}}$  represent the concentrations of Cr in the diets or feces and  $\text{nutrient}_{\text{feces}}$  or  $\text{nutrient}_{\text{diet}}$  represent the concentrations of nutrient in the diets or feces. Fecal N excretion per weight gain (g/kg) =  $[N \text{ intake (g/d)} \times (100 - \text{ATTD of N})] / [100 \times \text{ADG (kg/d)}]$ .

### Statistical Analysis

Data in Exp. 1 and 2 were analyzed using SAS (version 9.2; SAS Inst. Inc., Cary, NC) with a Student's *t*-test for unpaired data, with individual pig as an experimental unit. Performance and nutrient digestibility in Exp. 3 and 4 were analyzed with each pen as the experimental unit using GLM procedures of SAS followed by Tukey's multiple range tests. Differences in the fecal score were tested by the  $\chi^2$  contingency test. Treatment means were calculated using the LSMEANS statement. Statistically significant differences were declared at  $P < 0.05$ , and differences at  $0.05 \leq P < 0.10$  were considered a trend toward significance.

## RESULTS

### Energy Concentration in Exp. 1

There was no difference in DE and ME or ATTD of GE and OM between corn and sorghum grains (Table 5). The ATTD of CP in corn grain was greater than in sorghum grain ( $P < 0.05$ ).

### Digestible CP and Essential AA in Exp. 2

The AID and SID of CP and most EAA, with the exception of Val, Leu, and Phe, were greater ( $P < 0.05$ ) in corn than in sorghum (Table 6). There was no difference in total standardized ileal digestible EAA between the 2 grains, whereas the concentration of standardized ileal digestible CP in sorghum was lower

**Table 6.** Apparent ileal digestibility (AID) and standardized ileal digestibility (SID) of CP and essential AA (EAA) and concentration of Standardized ileal digestible CP and EAA in corn and sorghum grains (DM basis, Exp. 2)<sup>1</sup>

Item	Corn	Sorghum	SEM	<i>P</i> -value
AID value, %				
CP	59.48	54.07	1.76	0.04
Lys	58.40	50.62	1.68	0.03
Met	83.68	73.02	1.48	<0.01
Thr	56.98	51.66	1.32	0.04
Trp	58.22	54.98	1.05	0.04
Val	72.34	78.13	2.13	0.10
Leu	75.48	71.95	1.75	0.18
Ile	69.65	52.26	2.05	<0.01
Phe	64.88	63.45	2.02	0.82
His	62.65	54.15	1.85	0.02
Arg	69.56	61.53	2.22	0.04
SID value, %				
CP	72.48	65.42	2.26	0.04
Lys	74.80	66.39	1.80	0.03
Met	89.88	79.17	1.56	<0.01
Thr	79.82	74.54	1.32	0.04
Trp	85.22	70.53	2.50	<0.01
Val	85.34	87.25	1.45	0.78
Leu	82.48	81.95	1.55	0.69
Ile	81.56	73.26	1.78	0.01
Phe	75.88	72.68	2.02	0.74
His	82.86	77.08	1.38	0.04
Arg	86.68	78.99	2.46	0.04
Concentration, g/kg				
CP	65.21	59.57	1.89	0.04
Lys	1.95	1.59	0.08	0.03
Met	1.83	1.45	0.05	<0.01
Thr	2.63	2.55	0.03	0.04
Trp	0.58	0.56	0.05	0.25
Val	3.87	4.48	0.07	0.01
Leu	9.72	9.45	0.08	0.05
Ile	2.31	2.76	0.08	0.04
Phe	3.10	3.23	0.07	0.32
His	2.16	1.76	0.06	<0.01
Arg	3.04	3.06	0.04	0.78
Total	31.18	30.90	0.56	0.54

<sup>1</sup>Values for SID were calculated by correcting AID values with the basal endogenous losses. Basal endogenous losses averaged 20.90 g CP/kg DMI, 0.59 g Lys/kg DMI, 0.08 g Met/kg DMI, 0.67 g Thr/kg DMI, 0.14 g Trp/kg DMI, 0.51 g Val/kg DMI, 0.23 g Leu/kg DMI, 0.69 g Ile/kg DMI, 0.55 g Phe/kg DMI, 0.37 g His/kg DMI, and 0.95 g Arg/kg DMI.

than in corn ( $P < 0.05$ ). The concentrations of standardized ileal digestible Lys, Met, Thr, and His were lower in sorghum ( $P < 0.05$ ) whereas concentrations of standardized ileal digestible Val and Ile were greater than in corn ( $P < 0.05$ ).

**Table 7.** Effects of corn replacement with sorghum in diets fed to weaned pigs on growth performance and apparent total tract digestibility (ATTD) of nutrients (Exp. 3)<sup>1</sup>

Item	Corn:sorghum ratio				SEM	P-value
	60:0	40:20	20:40	0:60		
Performance						
d 1 to 14						
ADG, g	379	362	358	350	13.47	0.83
ADFI, g	568	551	549	536	18.60	0.70
G:F	0.668 <sup>a</sup>	0.655 <sup>b</sup>	0.652 <sup>b</sup>	0.651 <sup>b</sup>	0.003	0.04
Fecal score	2.94 <sup>a</sup>	2.84 <sup>b</sup>	2.83 <sup>b</sup>	2.85 <sup>b</sup>	—	0.04
d 15 to 28						
ADG, g	474	472	460	454	14.29	0.89
ADFI, g	817	816	802	798	33.76	0.93
G:F	0.581 <sup>a</sup>	0.579 <sup>a</sup>	0.573 <sup>ab</sup>	0.567 <sup>b</sup>	0.004	0.03
Fecal score	2.86	2.80	2.79	2.81	—	0.086
d 1 to 28						
ADG, g	428	415	408	401	11.08	0.84
ADFI, g	693	684	676	663	23.09	0.84
G:F	0.618 <sup>a</sup>	0.609 <sup>ab</sup>	0.605 <sup>b</sup>	0.603 <sup>b</sup>	0.004	0.04
Fecal score	2.90 <sup>a</sup>	2.82 <sup>b</sup>	2.82 <sup>b</sup>	2.83 <sup>b</sup>	—	0.02
ATTD of nutrients, %						
d 14						
DM	82.47	80.94	80.92	80.62	0.57	0.066
OM	85.89	84.52	84.46	84.14	0.50	0.082
GE	83.46	82.09	82.13	81.78	0.53	0.088
CP	79.08 <sup>a</sup>	76.87 <sup>b</sup>	74.89 <sup>c</sup>	74.76 <sup>c</sup>	0.74	0.01
d 28						
DM	81.01	81.46	81.46	81.37	0.41	0.83
OM	84.48	84.98	84.88	84.79	0.35	0.75
GE	81.56	82.33	81.83	81.81	0.44	0.66
CP	76.67 <sup>a</sup>	77.39 <sup>a</sup>	76.28 <sup>a</sup>	73.80 <sup>b</sup>	0.69	0.01

<sup>a-c</sup>Least squares means within a row with different superscripts differ ( $P < 0.05$ ).

<sup>1</sup>Values are least squares means for 6 pens per treatment.

### Growth Performance, Apparent Total Tract Digestibility of Nutrients, and Fecal Score of Weaned Pigs in Exp. 3

There was no difference in ADG and ADFI among the treatments during the experimental period (Table 7). The G:F and the ATTD of CP was decreased for pigs fed diets with sorghum in the first 2 wk ( $P < 0.05$ ) and for pigs fed diets containing 60% sorghum in the following 2 wk ( $P < 0.05$ ). The ATTD of DM ( $P = 0.066$ ), OM ( $P = 0.082$ ), and GE ( $P = 0.088$ ) tended to decrease for pigs fed diets with sorghum on d 14. The fecal score for pigs fed diets with sorghum, regardless of the substitute level, was less ( $P < 0.05$ ) or tended to be less ( $P = 0.086$ ) than that for pigs fed diets containing 60% corn.

**Table 8.** Growth performance and apparent total tract digestibility (ATTD) of nutrients of growing pigs fed diets based on corn and soybean meal (CSBM) or sorghum and soybean meal (SSBM) supplemented without (–) or with (+) 150 mg/kg protease ( $1.5 \pm 0.4$  units/g of diet; Exp. 4)<sup>1</sup>

Item	CSBM	SSBM		SEM	P-value
		–	+		
Performance					
d 1 to 35					
ADG, g	738	730	756	15.7	0.36
ADFI, g	1,546	1,576	1,538	39.7	0.58
G:F	0.481 <sup>a</sup>	0.462 <sup>b</sup>	0.489 <sup>a</sup>	0.005	0.03
d 36 to 70					
ADG, g	789	810	815	18.6	0.68
ADFI, g	2,316	2,454	2,333	64.2	0.26
G:F	0.342	0.327	0.344	0.006	0.062
d 1 to 70					
ADG, g	758	769	784	15.4	0.52
ADFI, g	1,926	2,008	1,939	53.4	0.48
G:F	0.395	0.379	0.400	0.006	0.058
ATTD of nutrients, %					
d 35					
DM	83.46	81.70	82.70	0.64	0.066
OM	85.30	83.70	84.70	0.55	0.058
GE	82.90	80.80	82.40	0.62	0.052
CP	75.04 <sup>a</sup>	69.60 <sup>b</sup>	74.26 <sup>a</sup>	1.32	0.04
d 70					
DM	84.60 <sup>a</sup>	82.60 <sup>b</sup>	84.30 <sup>a</sup>	0.42	0.03
OM	86.32 <sup>a</sup>	84.70 <sup>b</sup>	86.32 <sup>a</sup>	0.50	0.04
GE	83.50 <sup>a</sup>	81.50 <sup>b</sup>	83.06 <sup>a</sup>	0.45	0.04
CP	79.72 <sup>a</sup>	68.60 <sup>c</sup>	75.60 <sup>b</sup>	1.28	<0.01

<sup>a-c</sup>Least squares means within a row with different superscripts differ ( $P < 0.05$ ).

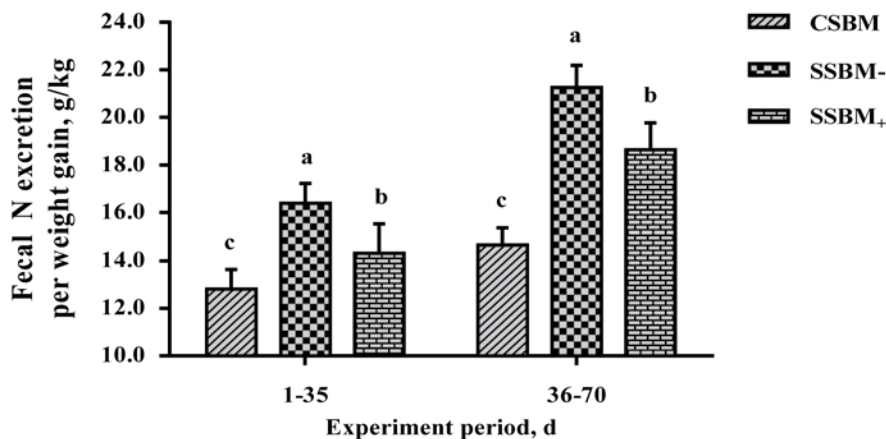
<sup>1</sup>Values are least squares means for 5 pens per treatment.

### Growth Performance of Growing Pigs and Effects of Protease on N Utilization in Exp. 4

No differences were observed in ADG and ADFI overall among the treatments (Table 8). Pigs fed CSBM or SSBM with protease had greater ( $P < 0.05$ ) or tended to have greater ( $P = 0.062$ ) G:F than pigs fed SSBM. The ATTD of DM, OM, and GE in CSBM tended to be greater on d 35 ( $P = 0.066$ ,  $P = 0.058$ , and  $P = 0.052$ , respectively) and was greater on d 70 ( $P < 0.05$ ) than that in SSBM.

Compared with CSBM, SSBM increased ( $P < 0.05$ ) fecal N excretion per weight gain by more than 25% and decreased ( $P < 0.05$ ) ATTD of CP by more than 7% during the whole experiment (Fig. 1). Protease supplementation reduced ( $P < 0.05$ ) fecal N excretion by more than 12% and increased ( $P < 0.05$ ) ATTD of CP by more than 6%.





**Figure 1.** Manure N output from growing pigs fed diets based on corn and soybean meal (CSBM) or sorghum and soybean meal (SSBM) supplemented without (SSBM<sup>-</sup>) or with 150 mg/kg protease ( $1.5 \pm 0.4$  units/g of diet; SSBM<sup>+</sup>) during 70 d period experiment (Exp. 4). Values are least squares means  $\pm$  SEM;  $n = 5$ /treatment. <sup>a-c</sup>Means with different superscripts significantly differ ( $P < 0.05$ ).

## DISCUSSION

As expected, the sorghum grain imported from the United States had low tannin concentration and had a chemical composition that was not different from corn grown in China, which was in line with the published results (NRC, 2012; Pan et al., 2016a; Stein et al., 2016; Xu et al., 2017). However, the nutritional value of sorghum is generally considered to be only 95% of that of corn (Hancock, 2000), despite the chemical composition of sorghum being similar to or even better than corn (Liu et al., 2013a). The concentration of starch and AA in sorghum is greater (Jaworski et al., 2015) but the digestibility was lower than in maize (Pedersen et al., 2007; Cervantes-Pahm et al., 2014a,b). Therefore, it is necessary to accurately evaluate DE and ME content (Exp. 1) and standardized ileal digestible AA concentration (Exp. 2) of corn and sorghum for formulating similar diets to compare the growth performance of weaned (Exp. 3) and growing pigs (Exp. 4) fed corn- or sorghum-based diets.

The DE and ME of corn and sorghum were close to the published values (NRC, 2012; Cervantes-Pahm et al., 2014a; Li et al., 2014; Pan et al., 2016a). As hypothesized, DE and ME values of U.S. sorghum were nearly equal to those of the corn produced in China, which was in agreement with reports that the concentration of GE in sorghum is similar to that in corn, and this is also the case for the concentration of DE and ME content (Cervantes-Pahm et al., 2014a; Bolarinwa and Adeola, 2016). The lack of a difference in apparent digestibility of DM, GE, and OM between the 2 grains is also in accordance with the published results (Cervantes-Pahm et al., 2014a; Lowell et al., 2015). It indicates that U.S. sorghum could replace Chinese corn as an energy source in term of the effective energy in this study. As a result, to compare effects of 2 different energy sources

(corn or sorghum) on growth performance of weaned or growing pigs (Exp. 3 and 4), sorghum directly replaced corn by different proportions without any additional energy supplementation in the diet formulation based on the similar DE content (Exp. 1).

The concentrations of AA in corn and sorghum used in the present experiment are within the range of published values (Pedersen et al., 2007; NRC, 2012; Stein et al., 2016). The AID and SID values obtained for corn and sorghum were less than values reported by the NRC (2012) but close to those for most EAA reported by Cervantes-Pahm et al. (2014b) and Stein et al. (2016). The variation may be the results of differences in cultivar, growing conditions, and antinutritional factors in grains (Fuller et al., 1989; Mariscal-Landín et al., 2004). The AID and SID values for corn were greater than those for sorghum, which were in line with published values (Pedersen et al., 2007; Stein et al., 2016). Amino acid digestibility in sorghum is negatively influenced by many factors including tannin (Jansman, 1993; Mariscal-Landín et al., 2004; Liu et al., 2013b), polyphenols (Liu et al., 2013c, 2016), kafirin (Selle et al., 2010; Liu et al., 2013a), phytate (Selle et al., 2003; Stein et al., 2016), and fiber (Bach Knudsen and Munck, 1985; Jaworski et al., 2015).

By taking the ileal digestibility of AA into consideration, a lack of available AA in compound feeds may be prevented while avoiding an excessive protein intake (Stein et al., 2007). Actually, the concentration of AA differs among cereal grains; therefore, the concentration of standardized ileal digestible AA may be more practical. The standardized ileal digestible AA concentration represents the amount of AA in the cereal grain that is assumed to be available for protein synthesis after absorption from the intestinal tract. The low contribution of standardized ileal digestible Lys, Met, and Thr from sorghum indicates that greater protein or AA

supplementation is needed when sorghum is used in diets than when corn is being used. The results also support the observation that more protein supplementation is required where sorghum is the major source of energy and protein in diets (Bwibo and Neumann, 2003). Therefore, more crystalline Lys, Met, and Thr were incorporated into diets based on sorghum than diets based on corn to meet the standardized ileal digestible EAA requirements for pigs in Exp. 3 and 4.

Sorghum may be used as the sole cereal grain to replace corn in diets fed to pigs without reducing the growth performance of weaned (Hongtrakul et al., 1998; Sotak et al., 2014; Woyengo et al., 2014), growing (Shelton et al., 2004), or finishing pigs (Benz et al., 2011; Paulk et al., 2015). In these studies, complete or partial substitution of corn with U.S. sorghum did not affect the feed intake, suggesting that the inclusion of sorghum had no effect on the palatability of the diets fed to weaned or growing pigs. There was no difference in ADG of weaned or growing pigs fed corn- and sorghum-based diets, which was in agreement with published data (Sotak et al., 2014; Paulk et al., 2015). Taking only the ADG and ADFI into consideration, sorghum may be equivalent to corn for weaned or growing pigs without negative effects on growth performance.

However, substituting sorghum for corn in diets reduced or tended to reduce G:F, for both weaned and growing pigs, especially for weaned pigs in the first 2 wk after weaning. In spite of no difference in ADG, a significant decrease in G:F was found in growing pigs fed SSBM relative to those fed CSBM (Shelton et al., 2004). The decrease in G:F was consistent with the decrease in nutrient digestibility, especially ATTD of CP, and the decrease in G:F and nutrient digestibility could be offset partially by protease supplementation in sorghum-based diets fed to growing pigs. Given the G:F and ATTD of CP in weaned pigs in the present study, the optimum inclusion of U.S. sorghum in diets should be less than 20% during the first 2 wk and no more than 40% during subsequent 2 wk after weaning.

Sorghum grain is not the preferred feed ingredient for pigs because of the poor digestibility of its protein in nonruminant animals (Selle et al., 2010). As shown in these 4 studies, the CP digestibility was lower for pigs fed diets based on sorghum than for pigs fed diets based on corn. As reviewed by Duodu et al. (2003), the poor protein digestibility in sorghum is due to an array of exogenous (grain structure, polyphenols, phytate, and cell wall components) and endogenous (disulfide crosslinking, kafirin hydrophobicity, and protein secondary structure) factors. Therefore, more work needs to be done to address the decreased CP digestibility in sorghum-based diets according to the corresponding factors.

In pigs, the decreased CP digestibility in sorghum-based diets would result in surplus N emission from animal manure (Yin et al., 1993; Yin, 1994; Pan et al., 2017), which may damage the natural environment (Pan et al., 2016c; Loss et al., 2017; Monteiro et al., 2017). Protease has been confirmed to improve N digestibility in monogastric animals (Piao et al., 1999; Liu et al., 2013a; Yu et al., 2016). Similarly, in this study, protease significantly increased the ATTD of CP by more than 6% and reduced fecal N excretion by more than 12%, which were similar to the values reported in recent studies that reported that proteases increased the ATTD of CP by more than 8% and decreased the fecal N excretion by more than 10% (Pan et al., 2017). Therefore, protease could improve N utilization by offsetting the increase in fecal N output for growing pigs fed sorghum-based diets, and supplementing with protease may be a potential way to address the low N utilization in sorghum-based diets.

It was interesting that the energy digestibility responded to the protease, which was in accordance with similar reports that exogenous proteases could improve the protein and energy utilization in sorghum (Liu et al., 2013c; Selle et al., 2013; Pan et al., 2017; Xu et al., 2017). It may be related to the unique structure of protein bodies that the kafirin protein fraction could impede protein and energy utilization because of its inherent hydrophobicity and disulfide cross-linking (Duodu et al., 2003; Salinas et al., 2006; Selle et al., 2010; Liu et al., 2013c). It follows that any improvements in protein digestibility may indirectly enhance the digestion of energy in sorghum (Selle et al., 2010; Liu et al., 2013c). Results indicated that protease supplementation with the capacity to degrade kafirin may be beneficial to energy utilization. The improved ATTD of nutrients perhaps resulted in the trend toward the increased G:F for pigs fed sorghum-based diets supplemented with protease.

The fecal score reflected the clinical signs of diarrhea, and the higher the fecal score is, the worse the diarrhea (Pan et al., 2016b). The fecal score was decreased in diets with inclusion of sorghum, irrespective of the substitute proportion. Unfortunately, few comparable studies have been completed to compare effects of diets based on corn and sorghum on fecal scores in weaned pigs. The exact mechanism is unclear, and it may be associated with the polyphenols in sorghum grain. Polyphenol extracts differ in properties, and some may reduce *Escherichia coli*-induced diarrhea for postweaning pigs, most likely by inactivating labile toxins (Verhelst et al., 2010, 2014). Polyphenol-containing plants are widely used as additives in various feed or food products because of their antioxidative (Lu et al., 2011) and antibacterial properties (Gordon and Wareham, 2010). Furthermore, plant polyphenols have been reported to

inactivate enterotoxin in vitro (Morinaga et al., 2005). In clinical medicine, a sorghum-based oral rehydration solution may be used as an alternative in the treatment of diarrhea (Pelleboer et al., 1990; Mustafa et al., 1995). Even so, further studies are needed to verify the positive effect and to determine if sorghum may provide a new approach to alleviating diarrhea in weaned pigs.

In conclusion, to meet dietary requirements for EAA in pigs, diets based on sorghum require more EAA supplementation, especially Lys, Met, and Thr, than diets based on corn in these studies, although sorghum has a DE and ME content and total standardized ileal digestible EAA composition similar to that of corn. Corn may be substituted with sorghum in diets fed to weaned or growing pigs without negative effects on growth performance. The inclusion of sorghum in diets may alleviate diarrhea in weaned pigs, but given the optimal G:F and N digestibility, less than 20% sorghum during the first 2 wk and no more than 40% during the subsequent 2 wk after weaning is recommended. Sorghum used as an alternative energy source for corn in growing pig diets could increase manure N output and thus decrease N utilization, and this could be addressed, at least partially, by protease supplementation. In terms of only one source of sorghum and corn used in these studies and the variability among different sources of the same cereal grains, further investigation is warranted to confirm the above results.

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