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Non Ruminant Nutrition

NON RUMINANT NUTRITION

Corn protein has greater concentrations of digestible amino acids and energy than low-oil corn distillers dried grains with solubles when fed to pigs but does not affect the growth performance of weanling pigs

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Abstract

Three experiments were conducted to test the hypothesis that standardized ileal digestibility (**SID**) of amino acids (**AA**) and digestible energy (**DE**) and metabolizable energy (**ME**) in a new source of corn protein are greater than in corn distillers dried grains with solubles (**DDGS**) and that corn protein may be included in diets for weanling pigs. In experiment 1, the SID of AA was determined in two sources of DDGS (DDGS-1 and DDGS-2) and in corn protein. Results indicated that SID of most AA was greater ($P < 0.05$) in DDGS-2 and corn protein than in DDGS-1, but corn protein contained more digestible AA than both sources of DDGS. In experiment 2, the DE and ME in corn, the two sources of DDGS, and corn protein were determined. Results demonstrated that DE (dry matter basis) in corn protein was greater ($P < 0.05$) than in corn, but ME (dry matter basis) was not different between corn and corn protein. However, DE and ME in corn (dry matter basis) were greater ($P < 0.05$) than in DDGS-1 and DDGS-2. In experiment 3, 160 weanling pigs were allotted to four treatments in phases 1 and 2 and a common diet in phase 3. Corn protein was included at 5% to 10% in phases 1 and 2 at the expense of plasma protein and enzyme-treated soybean meal. Results indicated that although differences in average daily gain and gain to feed ratio were observed in phase 1, no differences among treatments were observed for the overall experimental period. In conclusion, the concentration of digestible AA is greater in corn protein than in DDGS; DE and ME in corn protein are also greater than in DDGS; and up to 10% corn protein may be included in phase 1 and phase 2 diets for weanling pigs.

Key words: amino acid digestibility, corn protein, distillers dried grains with solubles, energy digestibility, growth performance, pigs

Abbreviations

AA	amino acids
ADFI	average daily feed intake
ADG	average daily gain
AID	apparent ileal digestibility
ATTD	apparent total tract digestibility
DDGS	distillers dried grains with solubles
DE	digestible energy
ESBM	enzyme-treated soybean meal
G:F	gain to feed ratio
ME	metabolizable energy
ND	not detected
SID	standardized ileal digestibility

Introduction

Animal protein sources such as fish meal and plasma protein that have high concentrations of digestible amino acids (**AA**) are often included in diets for weanling pigs (Kim and Easter, 2001; Jones et al., 2010; Almeida et al., 2013b). However, the reduced availability and rising cost of these feed ingredients have increased the need to identify alternative protein sources that weanling pigs can tolerate.

Corn distillers dried grains with solubles (**DDGS**) is a coproduct from the ethanol industry that can be included in diets for pigs (Whitney and Shurson, 2004; Zhu et al., 2010; Tran et al., 2012). The nutritional value of other high-protein corn coproducts such as corn gluten meal (Almeida et al., 2011; Rojas et al., 2013) and high-protein DDGS (Kim et al., 2009; Espinosa and Stein, 2018; Cristobal et al., 2020) has been reported. The digestibility of AA in corn coproducts is close to that in corn grain and the concentration of digestible energy (**DE**) and metabolizable energy (**ME**) is often greater than in corn grain (Rojas et al., 2013). However, the use of new technology in the dry-grind ethanol industry allows for fractionation of the whole stillage by mechanically separating some of the nonprotein components from the protein, which results in production of a new coproduct containing approximately 50% crude protein. At this point, no data to demonstrate the nutritional value of corn protein produced by processing the whole stillage to increase protein concentration have been reported. Therefore, the first objective of this research was to test the hypothesis that the standardized ileal digestibility (**SID**) of crude protein and AA and concentrations of DE and ME in corn protein are greater than in DDGS when fed to pigs. The second objective was to test the hypothesis that corn protein may be included in diets for weanling pigs at the expense of other protein sources without reducing growth performance.

Materials and Methods

Protocols for three experiments were submitted to the Institutional Animal Care and Use Committee at the University of Illinois (Urbana, IL), and all protocols were approved prior to initiation of the animal work of each experiment. Pigs that were used in the three experiments were the offspring of Line 359 boars mated to Camborough females (Pig Improvement Company, Hendersonville, TN). One batch of corn, two sources of DDGS (DDGS-1 and DDGS-2), and corn protein (NexPro; Flint Hills Resources, Wichita, KS) were used in experiments 1 and 2 (Table 1). Corn, soybean meal, DDGS, enzyme-treated soybean meal (**ESBM**; HP 300, Hamlet Protein, Finlay, OH), plasma protein (APC Inc., Ankeny, IA), rolled oats, and corn protein were used in experiment 3. The corn protein used in all experiments and the two sources of DDGS used in experiments 1 and 2 were sourced from Flint Hills Resources (Wichita, KS), but different batches of corn protein and DDGS were used in experiment 3. In all three experiments, diets were fed as a meal.

Experiment 1: AA digestibility

Animals and experimental procedures

Eight barrows (initial body weight: 37.13 ± 2.44 kg) that had a T-cannula installed in the distal ileum were used (Stein et al., 1998). Pigs were housed in individual pens (1.2 × 1.5 m) with smooth, plastic-coated sides and fully slatted tribar metal floors in an environmentally controlled room. Each pen had a feeder and a nipple drinker. Pigs were allotted to a replicated 4 × 4 Latin square design with four diets and four 7-d periods (Kim and Stein, 2009). There were two pigs per diet in each period for a total of eight replicates per treatment. Three diets were based on each of the two sources of DDGS or corn protein as the only AA-containing ingredient, and a nitrogen-free diet was used as well (Table 2). Chromic oxide (0.40%) was included in all diets as an indigestible marker, and vitamins and minerals were included in all diets to meet nutrient requirement estimates (NRC, 2012).

Pigs were fed their respective diets at 3.2 times the maintenance requirement for ME (i.e., 197 kcal ME per kg body weight$^{0.60}$; NRC, 2012), and water was available at all times. Body weights of pigs were recorded at the beginning of each period and at the conclusion of the experiment. Treatment diets were fed for a total of 7 d. The initial 5 d of each period was considered an adaptation period to the diets and ileal digesta were collected on days 6 and 7 for 8 h using standard procedures (Stein et al., 1998). Cannulas were opened at the beginning of collection and a 225-mL plastic bag was attached to the cannula barrel using a cable tie. Digesta flowing into the bag were collected and bags were replaced whenever they were full or at least once every 30 min. Digesta samples were stored at −20 °C immediately after collection. At the conclusion of the experiment, ileal digesta samples were thawed and mixed within pigs and diets, and a subsample was collected for chemical analysis.

Chemical analyses

Digesta samples were lyophilized and ground through a 1-mm screen (Wiley Mill Model 4; Thomas Scientific; Swedesboro, NJ). Ingredient, diet, and ileal digesta samples were analyzed for dry matter (method 930.15; AOAC Int, 2007), and nitrogen was analyzed using the combustion procedure (method 990.03; AOAC Int, 2007) on an Elementar Rapid N-cube protein/nitrogen apparatus (Elementar Americas Inc., Mt. Laurel, NJ). Aspartic acid was the calibration standard. Crude protein was calculated as 6.25 × nitrogen. AA were analyzed in ingredient, diet, and ileal digesta samples on a Hitachi AA Analyzer (Model No. L8800; Hitachi High Technologies America, Inc., Pleasanton, CA) using ninhydrin for postcolumn derivatization and norleucine as the internal standard (method 982.30 E [a, b, c]; AOAC Int, 2007). Chromium concentration in diet and ileal digesta samples was determined (method 990.08; AOAC Int, 2007) using inductively coupled plasma atomic emission spectroscopy (Avio 200; PerkinElmer, Waltham, MA). Ingredient samples were analyzed for gross energy using bomb calorimetry (Model 6300; Parr Instruments, Moline, IL), for ash (method 942.05; AOAC Int, 2007), and for acid-hydrolyzed ether extract by acid hydrolysis using 3N HCl (Ankom HCl Hydrolysis System, Ankom Technology, Macedon,

Table 1. Analyzed nutrient composition of ingredients (as-fed basis) used in experiments 1, 2, and 3[1]

Item	Experiments 1 and 2				Experiment 3						
	Corn	DDGS-1	DDGS-2	Corn protein	Corn	Soybean meal	Rolled oats	DDGS	Plasma protein	ESBM	Corn protein
Gross energy, kcal/kg	3,773	4,615	4,671	4,937	3,874	4,213	4,202	4,313	4,672	4,473	4,956
Dry matter, %	86.8	87.9	90.6	93.0	86.97	88.88	91.20	85.54	90.67	92.52	93.43
Ash, %	1.10	5.22	5.84	7.9	1.12	6.46	1.71	5.11	7.61	6.63	3.04
Acid-hydrolyzed ether extract, %	3.43	8.94	8.40	5.6	3.63	3.56	7.45	9.32	1.21	1.81	6.06
Insoluble dietary fiber, %	—	32.2	42.80	24.4	10.10	17.50	5.71	33.76	—	21.33	33.30
Soluble dietary fiber, %	—	2.00	1.90	3.4	ND[2]	2.80	5.60	2.34	—	3.51	2.52
Total dietary fiber, %	—	34.2	44.70	27.8	10.10	20.30	11.31	36.10	—	24.84	35.82
Crude protein, %	7.30	26.14	27.47	50.1	6.95	46.40	13.89	26.82	75.00	54.44	47.98
Lys-to-crude protein, %	—	2.91	2.66	4.0	3.46	6.29	4.38	2.87	9.15	5.60	3.59
Indispensable AA, %											
Arg	—	1.15	1.12	2.31	0.34	3.32	0.94	1.2	4.37	3.77	2.09
His	—	0.68	0.71	1.33	0.2	1.2	0.32	0.72	2.31	1.4	1.27
Ile	—	1.06	1.05	2.19	0.25	2.22	0.56	1.10	2.43	2.63	2.11
Leu	—	3.08	3.35	5.68	0.78	3.56	1.07	3.14	7.12	4.14	5.76
Lys	—	0.76	0.73	1.98	0.24	2.92	0.61	0.77	6.86	3.05	1.72
Met	—	0.48	0.51	1.01	0.14	0.64	0.26	0.54	0.86	0.75	1.14
Phe	—	1.32	1.39	2.49	0.34	2.42	0.76	1.37	4.05	2.78	2.54
Thr	—	0.98	0.98	2.00	0.25	1.79	0.47	0.99	4.95	2.09	1.89
Trp	—	0.19	0.18	0.42	0.05	0.61	0.13	0.17	1.61	0.69	0.35
Val	—	1.34	1.33	2.83	0.34	2.29	0.76	1.40	5.35	2.79	2.68
Dispensable AA, %											
Ala	—	1.81	1.99	3.47	0.50	1.99	0.66	1.84	3.73	2.34	3.46
Asp	—	1.61	1.62	3.55	0.48	5.21	1.13	1.75	7.73	6.00	3.53
Cys	—	0.46	0.50	0.87	0.15	0.66	0.45	0.52	2.51	0.77	0.96
Glu	—	3.57	4.25	7.39	1.22	8.40	2.98	3.89	10.55	9.64	7.98
Gly	—	1.02	1.04	2.01	0.30	1.95	0.70	1.04	2.66	2.30	1.87
Pro	—	1.94	2.15	3.50	0.58	2.38	0.75	2.08	3.82	2.69	3.72
Ser	—	1.13	1.15	2.17	0.32	2.08	0.62	1.16	4.53	2.39	2.13
Tyr	—	1.00	1.01	1.98	0.20	1.70	0.45	0.99	3.80	1.95	2.01

[1]DDGS = distillers dried grains with solubles (Flint Hills Resources, Wichita, KS); corn protein (Flint Hills Resources, Wichita, KS); ESBM (Hamlet Protein, Finlay, OH).
[2]ND, not detected.

NY) followed by fat extraction (Ankom XT-15 Extractor, Ankom Technology, Macedon, NY). Insoluble dietary fiber and soluble dietary fiber were analyzed in ingredient samples according to method 991.43 (AOAC Int, 2007) using the Ankom^{TDF} Dietary Fiber Analyzer (Ankom Technology, Macedon, NY). Total dietary fiber was calculated as the sum of insoluble and soluble dietary fiber.

Table 2. Ingredient and analyzed composition of diets used in experiment 1, as-fed basis[1]

Item	DDGS-1	DDGS-2	Corn protein	Nitrogen-free
Ingredient, %				
DDGS-1	50.00	—	—	—
DDGS-2	—	50.00	—	—
Corn protein	—	—	28.00	—
Soybean oil	2.00	2.00	2.00	4.00
Ground limestone	0.80	0.80	0.50	0.45
Dicalcium phosphate	0.90	0.90	1.40	2.15
Sucrose	—	—	—	20.00
Cornstarch	45.20	45.20	67.00	67.80
Solka floc[2]	—	—	—	4.00
Magnesium oxide	—	—	—	0.10
Potassium carbonate	—	—	—	0.40
Sodium chloride	0.40	0.40	0.40	0.40
Chromic oxide	0.40	0.40	0.40	0.40
Vitamin–mineral premix[3]	0.30	0.30	0.30	0.30
Analyzed dry matter and nutrients, %				
Dry matter	89.32	90.74	95.99	95.58
Crude protein	12.41	13.88	14.71	0.25
Indispensable AA				
Arg	0.53	0.56	0.66	0.01
His	0.33	0.36	0.39	<0.01
Ile	0.49	0.51	0.64	0.02
Leu	1.48	1.65	1.68	0.04
Lys	0.38	0.38	0.58	0.02
Met	0.23	0.25	0.30	0.02
Phe	0.61	0.66	0.74	0.02
Thr	0.47	0.49	0.58	0.01
Trp	0.11	0.11	0.15	0.02
Val	0.64	0.67	0.82	<0.01
Dispensable AA				
Ala	0.89	1.01	1.04	0.02
Asp	0.82	0.85	1.07	0.04
Cys	0.22	0.25	0.25	0.02
Glu	2.00	2.31	2.34	0.03
Gly	0.49	0.54	0.60	0.01
Pro	1.03	1.10	1.07	0.07
Ser	0.54	0.57	0.64	0.01
Tyr	0.43	0.47	0.52	0.02

[1]DDGS = distillers dried grains with solubles (Flint Hills Resources, Wichita, KS); corn protein (Flint Hills Resources, Wichita, KS).
[2]Fiber Sales and Development Corp., Urbana, OH.
[3]Provided the following quantities of vitamins and microminerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 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 B_{12}, 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 sulfate and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydroiodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

Calculations and statistical analyses

Values for apparent ileal digestibility (**AID**), basal ileal endogenous losses, and SID of crude protein and AA in each of the AA-containing diets were calculated (Stein et al., 2007). The AID and SID of crude protein and AA in the diets containing DDGS or corn protein represent the AID and SID of crude protein and AA in each source of DDGS and in corn protein because DDGS and corn protein were the sole sources of crude protein and AA in these diets.

Data were analyzed using the mixed linear model procedure of SAS (SAS Inst. Inc., Cary, NC). Homogeneity of variances was confirmed by conducting univariate analysis with outliers tested using the boxplot procedure. One pig fed one of the DDGS diets was removed from the data set because the mean for most of the AA deviated from the treatment mean by more than three times the interquartile range. The model included diet as the fixed effect, whereas pig, period, and square were random effects. Least squares means were calculated for each independent variable, and if significant, means were separated with Tukey's adjustment for pairwise comparison. Pig was the experimental unit and results were considered significant at $P \leq 0.05$.

Experiment 2: energy measurements

Animals and experimental procedures

Thirty-two barrows (initial body weight: 16.50 ± 0.90 kg) were allotted to four diets using a completely randomized design. Pigs were placed in individual metabolism crates that were equipped with a self-feeder, a nipple waterer, and slatted floors to allow for the total, but separate, collection of urine and feces. A basal diet containing corn as the sole source of energy and three diets containing corn and each source of DDGS or corn protein were formulated; thus, a total of four diets were used (Table 3). Vitamins and minerals were included in all diets to meet or exceed nutrient requirement estimates (NRC, 2012).

Feed was provided in a daily amount equal to 3.2 times the estimated ME requirement for maintenance, which was equally divided into two meals that were fed at 0800 and 1600 hours. Pigs had free access to water. Feed consumption was recorded daily. The initial 5 d was considered the adaptation period to the diet, whereas urine and feces were collected during the following 5 d using the marker-to-marker approach (Adeola, 2001). Feces were collected twice daily and urine was collected once daily. Urine collection buckets contained a preservative of 50 mL of 6N HCl. Feces and 20% of the collected urine were stored at −20 °C immediately after collection.

Chemical analyses

At the conclusion of the experiment, urine samples were thawed and mixed within pigs, and a subsample was lyophilized before analysis (Kim et al., 2009). Fecal samples were thawed and mixed within pigs and then dried in a 50 °C forced-air drying oven prior to analysis. Diets, fecal samples, and lyophilized urine samples were analyzed for gross energy as explained for experiment 1. Diet and fecal samples were analyzed for dry matter, and diet samples were analyzed for crude protein as explained for experiment 1.

Calculations and statistical analyses

The apparent total tract digestibility (**ATTD**) of gross energy and concentrations of DE and ME were calculated for each diet and

Table 3. Ingredient and analyzed composition of diets used in experiment 2, as-fed basis[1]

Item	Corn	DDGS-1	DDGS-2	Corn protein
Ingredient, %				
Ground corn	97.00	47.40	47.40	69.20
DDGS-1	—	50.00	—	—
DDGS-2	—	—	50.00	—
Corn protein	—	—	—	28.00
Ground limestone	0.80	1.30	1.30	1.10
Dicalcium phosphate	1.50	0.60	0.60	1.00
Sodium chloride	0.40	0.40	0.40	0.40
Vitamin–mineral premix[2]	0.30	0.30	0.30	0.30
Analyzed dry matter and nutrients, %				
Gross energy, kcal/kg	3,681	4,087	4,114	4,014
Dry matter, %	86.6	87.9	89.0	89.2
Crude protein, %	5.2	12.5	14.1	15.8

[1]DDGS = distillers dried grains with solubles (Flint Hills Resources, Wichita, KS); corn protein (Flint Hills Resources, Wichita, KS).
[2]Provided the following quantities of vitamins and micro-minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 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 B_{12}, 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 sulfate and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydroiodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

the DE and ME in the corn-based diet were used to calculate the DE and ME in corn. The contribution of DE and ME from corn to the DE and ME in the other three diets was then calculated, and the ATTD of gross energy and DE and ME in each source of DDGS and corn protein were calculated using the difference method (Adeola, 2001).

Data were analyzed as a completely randomized design with pig as the experimental unit. Homogeneity of variances was confirmed as explained for experiment 1, and data were analyzed as described for experiment 1. Data were tested for outliers as explained for experiment 1, but no outliers were detected. Diet or ingredient was the fixed effect. Least squares means were calculated and separated as described for experiment 1. Results were considered significant at $P < 0.05$.

Experiment 3: growth performance

Animals and experimental procedures

A total of 160 newly weaned pigs (initial body weight: 6.02 ± 0.84 kg) were used in a completely randomized design and allotted to one of the four treatments. Four different diets were fed in phases 1 and 2, whereas all pigs were fed a common diet in phase 3. Therefore, a total of nine diets were formulated (Table 4). There were five pigs per pen with eight replicate pens per treatment. Phase 1 diets were fed from day 1 to 7, phase 2 diets were fed from day 8 to 21, and the common phase 3 diet was provided from day 22 to 35. In phases 1 and 2, corn protein was included by up to 10% at the expense of plant and/or animal protein sources. The control diet in phase 1 was formulated without corn protein and contained 5% ESBM and 2.5% plasma protein. Two additional diets were formulated by replacing either plasma protein or ESBM with 5% corn protein, and one diet was formulated by replacing both plasma protein and ESBM with 10% corn protein. In phase 2, the control diet contained 7.5% ESBM and no plasma or corn protein. Three additional diets were formulated to contain 2.5%, 7.5%, or 10% corn protein at the expense of ESBM. All phase 1 diets contained 5% DDGS and phase 2 diets contained 7.5% DDGS. The common phase 3 diet was based on corn, soybean meal, and 10% DDGS. All diets in phases 1, 2, and 3 were formulated to meet the nutrient requirements of weanling pigs (NRC, 2012). Inclusion of crystalline AA was adjusted to maintain consistent concentrations of standardized ileal digestible AA among diets.

Individual body weights of pigs were recorded at the beginning of the experiment and at the conclusion of each phase. Feed additions were recorded daily and the weight of feed left in the feeder was recorded at the conclusion of each phase. Fecal scores were assessed visually per pen every other day using a subjective score ranging from 1 to 5 according to the method of Espinosa et al. (2017): 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 greater than or equal to 3 divided by the total number of pen days multiplied by 100, with pen days referring to the number of pens multiplied by the number of days assessing diarrhea scores. At the conclusion of the experiment, data were summarized to calculate average daily feed intake (**ADFI**), average daily gain (**ADG**), and gain to feed ratio (**G:F**) within pen and treatment group. Data were summarized for day 1 to 7, 8 to 21, 22 to 35, and for the entire experiment.

Chemical analyses

All diet samples were ground through a 1-mm screen in a Wiley mill (model 4; Thomas Scientific, Swedesboro, NJ) prior to analysis. Diets and ingredients were analyzed for dry matter, ash, gross energy, acid-hydrolyzed ether extract, crude protein, and AA, as explained for experiment 1. Calcium and P were analyzed in all diets (method 985.01 A, B, and C; AOAC Int, 2007) using inductively coupled plasma-optical emission spectrometry (Avio 200, PerkinElmer, Waltham, MA). Sample preparation included dry ashing at 600 °C for 4 h (method 942.05; AOAC Int, 2007) and wet digestion with nitric acid. Ingredients were also analyzed for insoluble and soluble dietary fiber, and total dietary fiber was calculated for each ingredient as explained for experiment 1.

Statistical analysis

Data were analyzed using the mixed linear model procedure of SAS with the pen as the experimental unit. Homogeneity of variances was confirmed and outliers were tested as described for experiment 1. One pen fed the control diet had results that deviated from the treatment mean by more than three times the interquartile range, and data for this pen were removed. The model included diet as a fixed effect. Means were calculated and separated as explained for experiment 1. The frequency procedure of SAS was used to analyze the frequency of diarrhea. Results were considered significant at $P \le 0.05$ and considered a trend at $P \le 0.10$.

Results

Experiment 1: AA digestibility

The AID of crude protein and most AA was greater ($P < 0.05$) in DDGS-2 and corn protein compared with DDGS-1 with the exception that the AID of Trp was not different among ingredients (Table 5). The AID of Leu was greater ($P < 0.05$) in DDGS-2 compared with DDGS-1 and corn protein. Greater

Table 4. Ingredients and analyzed dry matter, energy, and nutrients in diets used in experiment 3, as-fed basis[1]

	Phase 1 diets				Phase 2 diets				
Item, %	No corn protein	No ESBM	No plasma protein	Only corn protein	No corn protein	5% ESBM	1% ESBM	Only corn protein	Phase 3
Ingredient, %									
Ground corn	28.33	27.52	25.69	24.51	49.47	49.08	47.51	45.98	53.40
Rolled oats	20.00	20.00	20.00	20.00	—	—	—	—	—
Soybean meal	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00	30.00
Corn DDGS	5.00	5.00	5.00	5.00	7.50	7.50	7.50	7.50	10.00
Whey, dried	15.00	15.00	15.00	15.00	10.00	10.00	10.00	10.00	—
ESBM	5.00	—	4.50	—	7.50	5.00	1.00	—	—
Plasma protein	2.50	2.50	—	—	—	—	—	—	—
Corn protein	—	5.00	5.00	10.00	—	2.50	7.50	10.00	—
Soybean oil	1.08	1.72	1.50	2.04	2.55	2.85	3.32	3.38	3.68
Limestone	1.46	1.55	1.46	1.52	1.40	1.42	1.52	1.56	1.33
Dicalcium phosphate	0.28	0.20	0.30	0.25	0.20	0.18	0.10	0.05	0.30
L-Lys HCl	0.36	0.49	0.50	0.61	0.39	0.45	0.54	0.55	0.36
DL-Met	0.13	0.12	0.14	0.12	0.13	0.13	0.11	0.09	0.09
L-Thr	0.12	0.14	0.15	0.17	0.12	0.14	0.14	0.13	0.10
L-Trp	—	0.02	0.02	0.04	—	0.01	0.02	0.02	—
Phytase concentrate[2]	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Toxin binder[3]	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Salt	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
Vitamin–mineral premix[4]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Analyzed dry matter and nutrients, %									
Dry matter	89.47	89.44	90.08	90.21	87.94	88.07	88.43	87.76	86.88
Ash	6.16	5.55	6.04	5.64	5.28	5.47	4.90	4.40	4.81
Gross energy, kcal/kg	4,014	4,069	4,091	4,142	4,014	4,076	4,114	4,187	4,065
Crude protein	22.76	22.46	23.79	22.39	20.27	20.92	22.20	23.13	21.15
Acid-hydrolyzed ether extract	4.36	4.95	4.91	5.67	5.65	5.86	6.98	7.86	7.82
Ca	0.89	0.86	0.96	0.80	0.68	0.74	0.69	0.69	0.75
P	0.58	0.53	0.62	0.56	0.38	0.37	0.43	0.36	0.43
Indispensable AA									
Arg	1.31	1.26	1.39	1.23	1.16	1.39	1.12	1.31	1.35
His	0.54	0.54	0.58	0.54	0.51	0.61	0.52	0.59	0.57
Ile	0.95	0.94	1.07	0.98	0.89	1.08	0.91	0.95	0.94
Leu	1.86	1.93	2.05	2.05	1.80	2.16	1.94	2.10	1.90
Lys	1.64	1.69	1.82	1.78	1.34	1.53	1.39	1.64	1.37
Met	0.45	0.48	0.64	0.44	0.38	0.54	0.42	0.42	0.41
Phe	1.10	1.08	1.17	1.11	0.98	1.19	1.02	1.07	1.07
Thr	1.00	1.02	1.21	0.96	0.83	0.98	1.28	0.96	0.84
Trp	0.28	0.26	0.28	0.26	0.22	0.25	0.23	0.22	0.23
Val	1.14	1.15	1.19	1.12	0.98	1.19	1.02	1.11	1.06
Dispensable AA									
Ala	1.05	1.11	1.18	1.19	1.04	1.23	1.13	1.25	1.11
Asp	2.12	2.04	2.33	1.98	1.85	2.29	1.85	2.00	2.07
Cys	0.41	0.44	0.46	0.38	0.32	0.43	0.35	0.36	0.34

Table 4. Continued

Item, %	Phase 1 diets				Phase 2 diets				Phase 3
	No corn protein	No ESBM	No plasma protein	Only corn protein	No corn protein	5% ESBM	1% ESBM	Only corn protein	
Glu	3.80	3.79	4.12	3.91	3.47	4.22	3.58	3.87	3.77
Gly	0.87	0.87	0.94	0.88	0.79	0.93	0.80	0.90	0.89
Ser	0.98	0.99	1.05	0.99	0.85	1.02	0.89	0.97	0.93
Tyr	0.76	0.76	0.82	0.80	0.67	0.83	0.71	0.77	0.76

[1]DDGS = distillers dried grains with solubles (Flint Hills Resources, Wichita, KS); corn protein (Flint Hills Resources, Wichita, KS); ESBM = enzyme treated soybean meal (Hamlet Protein Inc., Findley, OH); plasma protein (APC Inc., Ankeny, IA).
[2]Phytase = Quantum Blue 5G (AB Vista, Marlborough, UK). The phytase concentrate contained 5,000 phytase units per gram. At 0.02% inclusion, the concentrate provided 1,000 units of phytase per kilogram of the complete diet.
[3]Toxin binder, hydrated sodium calcium aluminosilicate (United Animal Health, Sheridan, IN).
[4]Provided the following quantities of vitamins and micro-minerals per kilogram of complete diet: Vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 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 B_{12}, 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 dihydroiodide; 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.

Table 5. Apparent ileal digestibility of crude protein and AA in DDGS-1, DDGS-2, and corn protein fed to pigs, experiment 1[1,2]

Item	DDGS-1	DDGS-2	Corn protein	SEM	P-value
Crude protein	52.3^b	65.8^a	62.9^a	2.58	0.001
Indispensable AA					
Arg	59.2^b	75.2^a	71.0^a	3.36	0.002
His	68.3^b	76.5^a	76.0^a	1.25	<0.001
Ile	68.0^b	74.3^a	70.5^{ab}	1.27	0.007
Leu	80.4^b	86.0^a	82.8^b	0.91	0.002
Lys	46.1^b	53.9^a	56.0^a	1.95	0.003
Met	78.9^b	83.9^a	81.7^{ab}	0.94	0.002
Phe	74.2^b	79.7^a	77.4^{ab}	1.10	0.004
Thr	56.4^b	63.4^a	61.8^a	1.52	0.006
Trp	72.7	74.6	74.8	1.18	0.331
Val	63.5^b	72.3^a	68.9^a	1.47	0.001
Mean	68.8^b	76.5^a	73.2^a	1.19	0.001
Dispensable AA					
Ala	67.7^b	79.0^a	74.2^a	1.74	0.001
Asp	56.4^b	63.8^a	62.4^a	1.53	0.005
Cys	58.5^b	67.5^a	67.2^a	1.59	<0.001
Glu	75.6^b	83.0^a	79.9^a	1.25	0.002
Gly	5.8^b	40.6^a	39.2^a	8.29	0.003
Ser	66.1^b	73.0^a	69.7^{ab}	1.15	0.002
Tyr	76.0^b	81.0^a	77.9^{ab}	0.97	0.006
Mean	49.3^b	67.8^a	63.2^a	4.03	0.002
Total AA	58.1^b	71.7^a	67.8^a	2.52	0.001

[1]Data are least squares means of eight observations for each treatment, except for DDGS-2, for which data are the means of seven observations.
[2]DDGS = distillers dried grains with solubles (Flint Hills Resources, Wichita, KS); corn protein (Flint Hills Resources, Wichita, KS).
[a,b]Values within a row lacking a common superscript letter are different ($P < 0.05$).

($P < 0.05$) AID of Ile, Met, Phe, Ser, and Tyr in DDGS-2 compared with DDGS-1 was also observed.

The SID of crude protein and most AA was greater ($P < 0.05$) in DDGS-2 and corn protein compared with DDGS-1 (Table 6). The SID of Ile was greater ($P < 0.05$) in DDGS-2 compared with DDGS-1 and corn protein. The SID of Leu, Met, Phe, Thr, and the mean of indispensable AA in DDGS-2 was greater ($P < 0.05$) compared with DDGS-1 but was not different from corn protein. Concentrations of standardized ileal digestible crude protein and all AA except Trp were greater ($P < 0.01$) in corn protein compared with DDGS-1 and DDGS-2 (Table 7), but DDGS-2 had greater ($P < 0.01$) concentrations of standardized ileal digestible crude protein and all AA except Trp compared with DDGS-1.

Experiment 2: energy measurements

The gross energy excreted in feces from pigs fed DDGS-1 or DDGS-2 diets was greater ($P < 0.05$) compared with pigs fed the corn or corn protein diets, but pigs fed the corn diet had less ($P < 0.05$) gross energy excreted in urine compared with pigs fed the DDGS-1 or DDGS-2 diets (Table 8). The ATTD of gross energy was greater ($P < 0.05$) in the corn diet and in the corn protein diet than in DDGS-1 and DDGS-2 diets, but the ATTD of gross energy was greater ($P < 0.05$) in the DDGS-1 diet compared with the DDGS-2 diet. The concentration of DE was greater ($P < 0.05$) in the corn protein diet than in the two DDGS diets, whereas the concentration of ME did not differ between the corn protein diet and the corn diet. The DDGS-2 diet had the least ($P < 0.05$) concentration of DE among experimental diets, but the ME in DDGS-2 was not different from that of the DDGS-1 diet.

Table 6. Standardized ileal digestibility of crude protein and AA in DDGS-1, DDGS-2, and corn protein fed to pigs, experiment 1[1, 2, 3]

Item	DDGS-1	DDGS-2	Corn protein	SEM	P-value
Crude protein	65.2[b]	77.5[a]	74.6[a]	2.58	0.003
Indispensable AA					
Arg	70.6[b]	86.2[a]	80.9[a]	3.36	0.003
His	72.7[b]	80.6[a]	80.0[a]	1.25	<0.001
Ile	73.4[b]	79.5[a]	74.9[b]	1.27	0.007
Leu	83.2[b]	88.5[a]	85.4[ab]	0.91	0.002
Lys	53.7[b]	61.6[a]	61.4[a]	1.95	0.011
Met	81.5[b]	86.3[a]	83.8[ab]	0.94	0.003
Phe	78.2[b]	83.4[a]	80.9[ab]	1.10	0.006
Thr	65.4[b]	72.2[a]	69.7[ab]	1.52	0.010
Trp	80.0	82.1	80.6	1.18	0.438
Val	69.5[b]	78.2[a]	74.0[a]	1.47	0.001
Mean	74.3[b]	81.7[a]	77.9[ab]	1.19	0.001
Dispensable AA					
Ala	73.4[b]	84.0[a]	79.4[a]	1.74	0.001
Asp	63.9[b]	71.1[a]	68.5[ab]	1.53	0.008
Cys	64.3[b]	72.7[a]	72.7[a]	1.59	0.001
Glu	79.1[b]	86.1[a]	83.2[ab]	1.25	0.003
Gly	35.2[b]	67.7[a]	65.0[a]	8.29	0.005
Ser	73.6[b]	80.2[a]	76.5[ab]	1.15	0.003
Tyr	80.6[b]	85.2[a]	82.0[ab]	0.97	0.008
Mean	63.7[b]	81.0[a]	76.4[a]	4.03	0.004
Total AA	68.5[b]	81.4[a]	77.1[a]	2.52	0.001

[1]Data are least squares means of eight observations for each treatment, except for DDGS-2, for which data are the means of seven observations.
[2]SID values were calculated by correcting values for apparent ileal digestibility for the basal ileal endogenous losses. Basal ileal endogenous losses were determined as follows (g/kg dry matter intake): crude protein, 17.85; Arg, 0.68; His, 0.16; Ile, 0.29; Leu, 0.46; Lys, 0.32; Met, 0.07; Phe, 0.27; Thr, 0.48; Trp, 0.09; Val, 0.43; Ala, 0.56; Asp, 0.69; Cys, 0.14; Glu, 0.79; Gly, 1.61; Ser, 0.46; and Tyr, 0.22.
[3]DDGS = distillers dried grains with solubles (Flint Hills Resources, Wichita, KS); corn protein (Flint Hills Resources, Wichita, KS).
[a,b]Values within a row lacking a common superscript letter are different ($P < 0.05$).

Table 7. Concentrations (g/kg) of standardized ileal digestible (as-fed basis) crude protein and AA in DDGS-1, DDGS-2, and corn protein, experiment 1[1, 2]

Item	DDGS-1	DDGS-2	Corn protein	SEM	P-value
Crude protein	170.1[c]	211.9[b]	365.6[a]	8.74	<0.001
Indispensable AA					
Arg	8.1[c]	9.6[b]	17.8[a]	0.47	<0.001
His	4.9[c]	5.7[b]	10.4[a]	0.11	<0.001
Ile	7.8[b]	8.4[b]	16.1[a]	0.20	<0.001
Leu	25.6[c]	29.7[b]	48.8[a]	0.37	<0.001
Lys	4.1[b]	4.5[b]	11.4[a]	0.25	<0.001
Met	3.9[c]	4.4[b]	9.0[a]	0.07	<0.001
Phe	10.3[c]	11.6[b]	20.3[a]	0.20	<0.001
Thr	6.4[b]	7.1[b]	13.6[a]	0.22	<0.001
Trp	1.5[b]	1.5[b]	3.1[a]	0.03	<0.001
Val	9.3[c]	10.4[b]	20.4[a]	0.27	<0.001
Dispensable AA					
Ala	13.3[c]	16.7[b]	27.5[a]	0.40	<0.001
Asp	10.3[b]	11.5[b]	24.3[a]	0.40	<0.001
Cys	3.0[c]	3.6[b]	6.7[a]	0.10	<0.001
Glu	28.2[c]	36.6[b]	63.9[a]	0.64	<0.001
Gly	3.6[c]	7.0[b]	12.6[a]	1.01	<0.001
Ser	8.3[c]	9.2[b]	14.8[a]	0.17	<0.001
Tyr	8.1[c]	8.6[b]	15.9[a]	0.14	<0.001

[1]Data are least squares means of eight observations for each treatment, except for DDGS-2, for which data are the means of seven observations.
[2]DDGS = distillers dried grains with solubles (Flint Hills Resources, Wichita, KS); corn protein (Flint Hills Resources, Wichita, KS).
[a–c]Values within a row lacking a common superscript letter are different ($P < 0.05$).

Data calculated for each ingredient indicated that corn and corn protein had greater ($P < 0.05$) ATTD of gross energy compared with DDGS-1 and DDGS-2, whereas DDGS-1 had greater ($P < 0.05$) ATTD of gross energy compared with DDGS-2. Corn protein had greater ($P < 0.05$) DE (as-fed basis) than corn, DDGS-1, and DDGS-2; however, the concentration of DE in the two sources of DDGS was less ($P < 0.05$) than in corn with DDGS-1 having greater ($P < 0.05$) DE than DDGS-2. The ME (as-fed basis) in corn and corn protein was greater ($P < 0.05$) than in the two sources of DDGS. On a dry matter basis, the DE, but not the ME, in corn protein was greater ($P < 0.05$) than in corn; however, corn protein and corn had greater ($P < 0.05$) DE and ME than DDGS-1 and DDGS-2, and DDGS-1 had greater ($P < 0.05$) DE and ME than DDGS-2.

Experiment 3: growth performance

In phase 1, ADG and G:F of pigs fed the control diet were greater ($P < 0.05$) compared with pigs fed the diet containing ESBM and corn protein and the diet containing 10% corn protein, but no differences were observed for ADFI or final body weight (Table 9). Likewise, ADG, ADFI, G:F, and final body weight in phase 2, phase 3, and for the overall experimental period were not different among treatments.

Inclusion of corn protein did not affect fecal scores of pigs in phase 1, but in phase 2, diarrhea scores in pigs fed the diet containing 10% corn protein tended to be less ($P < 0.10$) compared with pigs fed the control diet (Table 10). Diarrhea frequency was less ($P < 0.05$) in phase 1 for pigs fed the diet containing 5% corn protein and plasma protein compared with pigs fed the diet with 5% corn protein and ESBM, but in phases 2 and 3, and during the overall experiment, no differences among treatments in diarrhea frequency were observed.

Discussion

Nutrient composition

The concentration of acid-hydrolyzed ether extract in the two DDGS sources used in experiments 1 and 2 was between 5% and 9%, indicating that these DDGS sources were low-oil DDGS (NRC, 2012; Stein et al., 2016). Concentrations of dry matter, crude protein, and most of the AA in the two sources of DDGS were in agreement with reported values (Stein et al., 2006; NRC, 2012; Adeola and Ragland, 2016; Stein et al., 2016). However, the concentration of Lys in both samples was less than reported for low-oil DDGS (NRC, 2012; Curry et al., 2014, 2016). The concentration of gross energy in DDGS-1 and DDGS-2 was in agreement with published data (NRC, 2012; Curry et al., 2016; Espinosa et al., 2019).

The reduced dietary fiber in corn protein compared with DDGS is the result of the mechanical separation of fiber from the protein that occurs during the production process. Front-end fractionation of the corn grain results in production of high-protein DDG or DDGS (i.e., 37% to 43% crude protein), which

Table 8. Concentration of DE and ME and ATTD of gross energy in experimental diets and in corn, DDGS-1, DDGS-2, and corn protein, experiment 2[1, 2]

Item	Corn	DDGS-1	DDGS-2	Corn protein	SEM	P-value
Diets						
Gross energy intake, kcal/d	2,884	3,306	3,196	3,165	153	0.273
Gross energy in feces, kcal/d	317[b]	749[a]	852[a]	427[b]	47	<0.001
Gross energy in urine, kcal/d	74[b]	168[a]	142[a]	133[ab]	17	0.004
ATTD of gross energy, %	89.0[a]	77.4[b]	73.6[c]	86.6[a]	0.8	<0.001
DE, kcal/kg	3,276[b]	3,165[b]	3,026[c]	3,476[a]	31	<0.001
ME, kcal/kg	3,181[a]	2,961[b]	2,845[b]	3,306[a]	41	<0.001
Ingredients						
ATTD of gross energy, %	89.0[a]	68.4[b]	60.9[c]	82.2[a]	1.2	<0.001
DE, kcal/kg	3,377[b]	3,128[c]	2,850[d]	4,070[a]	56	<0.001
ME, kcal/kg	3,279[a]	2,813[b]	2,581[b]	3,705[a]	76	<0.001
DE, kcal/kg dry matter	3,892[b]	3,558[c]	3,147[d]	4,374[a]	62	<0.001
ME, kcal/kg dry matter	3,779[a]	3,200[b]	2,850[c]	3,982[a]	86	<0.001

[1]Data are means of eight observations per treatment.
[2]DDGS = distillers dried grains with solubles (Flint Hills Resources, Wichita, KS); corn protein (Flint Hills Resources, Wichita, KS).
[a–d]Values within a row lacking a common superscript letter are different ($P < 0.05$).

is produced after de-hulled and de-germed corn have been fermented (Widmer et al., 2007). Concentrations of crude protein and AA in corn protein were greater than reported values for high-protein DDGS (Adeola and Ragland, 2016; Rho et al., 2017; Espinosa and Stein, 2018; Cristobal et al., 2020). The reason that crude protein is greater in corn protein than in conventional and high-protein DDGS is that after fermentation, a combination of spent yeast and corn gluten protein from the stillage are recovered together. The concentration of gross energy in corn protein concurs with values for high-protein DDGS (Widmer et al., 2007; Son et al., 2019; Cristobal et al., 2020). Concentrations of insoluble dietary fiber and soluble dietary fiber in corn protein were greater than reported by Cristobal et al. (2020) for high-protein DDGS but less than values reported by Espinosa and Stein (2018).

AA digestibility

The AID and SID of crude protein and all AA, except Lys, in the two DDGS sources were in agreement with reported values for low-oil DDGS (NRC, 2012; Curry et al., 2014; Stein et al., 2016; Espinosa et al., 2019). The Lys-to-crude protein ratio in DDGS-1 and DDGS-2 was 2.9% and 2.7%, respectively, indicating that these sources of DDGS may have been slightly heat damaged (Stein and Shurson, 2009; Espinosa et al., 2019). As a consequence, the AID and SID of Lys in the DDGS sources were less than what is usually observed in low-oil DDGS that is not heat damaged (Almeida et al., 2013a; Espinosa et al., 2019).

The two DDGS sources used in experiment 1 had concentrations of crude protein and AA that were not different and DDGS-1 contained less dietary fiber than DDGS-2; therefore, the observed reduction in SID of some AA in DDGS-1 compared with DDGS-2 was not expected. However, other dietary and processing factors may influence AA digestibility in DDGS and the SID of AA in both sources of DDGS used in this experiment were within the range of values previously reported (Stein and Shurson, 2009). The AID and SID of crude protein and AA in corn protein were within the range of values reported for high-protein DDGS (Adeola and Ragland, 2016; Rho et al., 2017; Espinosa and Stein, 2018; Son et al., 2019; Cristobal et al., 2020). The greater Lys-to-crude protein ratio in corn protein than in corn and DDGS is likely a result of the yeast that is included in the corn protein. During the fractionation process, the majority of the yeast from fermentation ends up in the corn protein fraction and because yeast protein has a greater concentration of Lys than corn protein, the end product has a greater Lys-to-crude protein ratio. The reason that corn protein contained more standardized ileal digestible AA if calculated as g/kg than both sources of DDGS, although the SID of AA was not greater than in DDGS-2, is that corn protein had greater concentrations of AA than the two sources of DDGS.

Energy measurements

Calculated values for DE and ME in corn were within the range of reported values (Kim et al., 2009; NRC, 2012; Curry et al., 2016). Concentrations of DE and ME in DDGS-1 were in agreement with values reported for low-oil DDGS, whereas DE and ME in DDGS-2 were less than published data (NRC, 2012; Curry et al., 2016), which may be due to the greater concentration of insoluble dietary fiber in DDGS-2. The DE and ME in corn protein were less than in some sources of high-protein DDGS (Rho et al., 2017; Espinosa and Stein, 2018), which is likely a result of the reduced concentration of acid-hydrolyzed ether extract in corn protein compared with high-protein DDGS. Likewise, concentrations of DE and ME in corn protein were less than in corn gluten meal (NRC, 2012; Rojas et al., 2013), which is because corn protein contains more insoluble fiber than corn gluten meal, and insoluble fiber reduces ME in feed ingredients (Urriola et al., 2010; Jaworski et al., 2015).

Despite greater AA digestibility compared with DDGS-1, the observed reduction in DE and ME in DDGS-2 is likely a result of increased concentration of dietary fiber, which subsequently resulted in reduced energy digestibility. The observation that corn protein had greater DE and ME compared with corn, DDGS-1, and DDGS-2 is likely a result of greater concentrations of gross energy, crude protein, and AA, and a reduction in insoluble dietary fiber compared with DDGS-1 and DDGS-2. Because pigs fed diets containing corn protein had reduced fecal output of gross energy compared with pigs fed DDGS-1 or DDGS-2, absorption of energy from corn protein was greater than from the two sources of DDGS

Table 9. Growth performance for pigs fed experimental diets, experiment 3[1]

	Diets[2,3]					
Item	No corn protein	No ESBM	No plasma protein	Corn protein	SEM	P-value
Phase 1 (day 1 to 7)						
Initial body weight, kg	5.857	6.028	6.020	6.024	0.281	0.964
ADG[4], kg	0.134[a]	0.106[ab]	0.088[bc]	0.074[c]	0.008	<0.001
ADFI[4], kg	0.162	0.146	0.147	0.136	0.008	0.176
G:F[4]	0.836[a]	0.731[ab]	0.604[bc]	0.538[c]	0.048	<0.001
Final body weight, kg	6.792	6.773	6.639	6.544	0.287	0.907
Phase 2 (day 8 to 21)						
ADG, kg	0.285	0.292	0.277	0.267	0.013	0.515
ADFI, kg	0.433	0.430	0.418	0.404	0.020	0.690
G:F	0.662	0.681	0.663	0.661	0.022	0.877
Final body weight, kg	10.777	10.860	10.513	10.282	0.377	0.655
Phase 3 (day 22 to 35)						
ADG, kg	0.554	0.552	0.572	0.566	0.016	0.748
ADFI, kg	0.837	0.848	0.851	0.859	0.024	0.932
G:F	0.663	0.653	0.672	0.662	0.020	0.903
Final body weight, kg	18.526	18.583	18.518	18.200	0.524	0.945
Overall phase (day 1 to 35)						
ADG, kg	0.362	0.359	0.357	0.348	0.010	0.759
ADFI, kg	0.541	0.540	0.537	0.533	0.018	0.984
G:F	0.673	0.666	0.666	0.656	0.018	0.919

[1]Data are least square means of eight observations for all treatments. ESBM = enzyme treated soybean meal (Hamlet Protein Inc., Findley, OH).
[2]Phase 1 diets, control diet contained 5% ESBM and 2.5% plasma protein; second diet contained 2.5% plasma protein and 5% corn protein; third diet contained 4.5% ESBM and 5% corn protein; and fourth diet contained 10% corn protein.
[3]Phase 2 diets, control diet contained 7.5% ESBM; second diet contained 5% ESBM and 2.5% corn protein; third diet contained 1% ESBM and 7.5% corn protein; and fourth diet contained 10% corn protein.
[4]Phase 3 diet, common corn–soybean meal diet.
[a–c]Values within a row lacking a common superscript letter are different ($P < 0.05$).

(NRC, 2012; Gutierrez et al., 2014). Therefore, it is likely that the reduced concentration of dietary fiber and the increased concentration of crude protein in corn protein resulted in increased concentrations of DE and ME, which is in agreement with data for high-protein DDGS (Rho et al., 2017; Espinosa and Stein, 2018; Cristobal et al., 2020). The observation that ME (dry matter basis) in corn and corn protein is not different demonstrates that corn protein provides the same amount of energy in diets as corn when fed to pigs.

Growth performance

Most diets for weanling pigs contain highly digestible plant and animal proteins (e.g., plasma protein, fish meal, or ESBM) to improve growth performance and intestinal health of pigs (Kim and Easter, 2001; Goebel and Stein, 2011). However, because of the emergence of new technologies in the dry-grind ethanol industry, it is now possible to produce corn protein ingredients with more than 50% crude protein (Cristobal et al., 2020). Corn protein may, therefore, be used as a non-soybean source of AA in diets for pigs where they may be used to partially or fully replace animal and/or plant proteins (Rao et al., 2020).

The observation that growth performance and fecal scores did not differ among treatments for the overall experiment indicates that protein utilization and growth performance are not affected by the inclusion of corn protein in diets for nursery pigs. These results are in contrast with data indicating that inclusion of up to 30% high-protein DDGS in diets for nursery pigs resulted in a reduction in growth performance (Yang et al., 2019). The reason for this discrepancy may be that a lower inclusion level of corn protein was used in the current experiment compared with the inclusion of high-protein DDGS in the experiment by Yang et al. (2019).

Corn protein has greater concentrations of standardized ileal digestible Met, Leu, and Val than soybean meal (NRC, 2012). However, a potential problem with the use of high-protein corn coproducts is that corn protein has a high concentration of Leu, which may negatively affect the metabolism of Val and Ile (Harris et al., 2004; Kwon et al., 2019; Yang et al., 2019). Excess Leu activates degradation pathways inducing catabolism of Leu, Val, and Ile, which can result in antagonism (Cemin et al., 2019; Yang et al., 2019). Likewise, Leu competes with Trp for transport into the brain, and excess dietary Leu may reduce the synthesis of serotonin and thereby reduce the feed intake of pigs (Kwon et al., 2019; Yang et al., 2019). However, the observation that ADFI was not negatively affected by corn protein indicates that if inclusion rates of corn protein in diets for weanling pigs do not exceed 10%, no negative effects of corn protein on feed intake are observed. The relatively high fiber content in corn protein may increase mucin secretion and Thr losses and thereby affect the requirement for Thr (Mathai et al., 2016). However, the lack of negative effects of corn protein on growth performance does not indicate that a Thr deficiency was induced. This supports the conclusion that at the inclusion rates used in this experiment, no negative effects of corn protein were observed.

Table 10. Fecal score and frequency of diarrhea for pigs fed the experimental diets, experiment 3[1]

	Diets[2,3,4]					
Item	No corn protein	No ESBM	No plasma protein	Corn protein	SEM	P-value
Fecal score[5]						
Phase 1 (day 1 to 7)	1.88	1.71	2.17	1.88	0.152	0.219
Phase 2 (day 8 to 21)	1.86[x]	1.70[xy]	1.55[xy]	1.50[y]	0.103	0.086
Phase 3 (day 22 to 35)	1.55	1.59	1.38	1.59	0.128	0.591
Overall phase (day 1 to 35)	1.76	1.67	1.70	1.66	0.075	0.739
Frequency of diarrhea						
Day 1 to 7 (phase 1)						
Pen days[6]	24	24	24	24		
Frequency[7]	20.83	4.17	41.67	16.67	—	0.014
Day 8 to 21 (phase 2)						
Pen days	56	56	56	56		
Frequency	21.43	12.5	14.29	8.93	—	0.285
Day 22 to 35 (phase 3)						
Pen days	56	56	56	56		
Frequency	3.57	5.36	0	5.36	—	0.375
Day 1 to 35 (overall phase)						
Pen days	136	136	136	136		
Frequency	13.97	8.09	13.24	8.82	—	0.290

[1]Data are least square means of eight observations for all treatments. ESBM = enzyme treated soybean meal (Hamlet Protein Inc., Findley, OH).
[2]Phase 1 diets, control diet contained 5% ESBM and 2.5% plasma protein; second diet contained 2.5% plasma protein and 5% corn protein; third diet contained 4.5% ESBM and 5% corn protein; and fourth diet contained 10% corn protein.
[3]Phase 2 diets, control diet contained 7.5% ESBM; second diet contained 5% ESBM and 2.5% corn protein; third diet contained 1% ESBM and 7.5% corn protein; and fourth diet contained 10% corn protein.
[4]Phase 3 diet, common corn–soybean meal diet.
[5]Fecal score, 1, normal feces; 2, moist feces; 3, mild diarrhea; 4, severe diarrhea; and 5, watery diarrhea.
[6]Pen days = number of pens × the number of days assessing diarrhea scores.
[7]Frequency = (number of pen days with diarrhea scores greater than or equal to 3/pen days) ×100.
[x,y]Values within a row lacking a common superscript letter tend to be different ($P < 0.10$).

Conclusions

Although the SID of crude protein and AA in the corn protein used in the present experiments was not greater than in one of the sources of DDGS, concentrations of digestible AA in corn protein were greater than in both sources of DDGS. Concentrations of gross energy, DE, and ME in corn protein were also greater than in low-oil DDGS. Pigs fed diets containing corn protein had reduced ADG during the initial week postweaning, but the inclusion of corn protein in diets did not affect growth performance in phases 1 and 2 or during the entire experimental period, indicating that corn protein may be included in diets for weanling pigs by up to 10%.

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Conflict of interest statement

The authors have no real or perceived conflicts of interest.

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