Animal Feed Science and Technology 280 (2021) 115040

Contents lists available at ScienceDirect

Animal Feed Science and Technology

journal homepage: www.elsevier.com/locate/anifeedsci

Digestibility of amino acids and concentration of metabolizable energy are greater in high-oil corn than in conventional corn when fed to growing pigs

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ARTICLE INFO

Keywords:
Amino acids
Corn
Digestibility
Energy
High-oil corn
Pigs

ABSTRACT

Two experiments were conducted to test the hypothesis that the coefficient of standardized ileal digestibility (CSID) of amino acids (AA), concentrations of digestible energy (DE) and metabolizable energy (ME), and the coefficient of standardized total tract digestibility (CSTTD) of phosphorus (P) in high-oil corn is greater than in conventional corn. In experiment 1, 9 pigs (81.5 ± 5.9 kg) that had a T-cannula installed in the distal ileum were allotted to a triplicated 3 × 3 Latin square design with 3 diets and 3 periods for 9 replicates per diet. A nitrogen-free diet and 2 diets that contained conventional corn or high-oil corn as the only source of crude protein (CP) and AA were formulated. Results indicated that the CSID of CP and most AA was greater ($P < 0.05$) in high-oil corn than in conventional corn, which consequently resulted in greater concentrations of standardized ileal digestible AA in high-oil than in conventional corn. In experiment 2, 64 pigs (18.75 ± 2.2 kg) were housed in metabolism crates and allotted to a 2 × 4 factorial arrangement with 2 sources of corn (conventional corn or high-oil corn) and 4 levels of microbial phytase (0, 500, 1000, or 2000 phytase units/kg). Feces and urine were collected using the marker-to-marker approach with 5-day adaptation and 4-day collection periods. The digestibility of gross energy (GE) was not different between diets containing high-oil corn and diets containing conventional corn. However, because of the greater GE in high-oil corn than in conventional corn, concentrations of DE and ME in high-oil corn were greater ($P < 0.01$) than in conventional corn. Addition of microbial phytase to diets increased ($P < 0.01$) the CSTTD of P in both corn sources, and the CSTTD of P was greater ($P < 0.01$) in high-oil corn than in conventional corn. In conclusion, high-oil corn contained more standardized ileal digestible AA, DE, and ME than conventional corn. The CSTTD of P in high oil corn, regardless of phytase supplementation, was also greater than in conventional corn. These results indicate that high-oil corn has greater nutritional value than conventional corn when fed to pigs.

Abbreviations: AA, amino acids; AEE, acid hydrolyzed ether extract; Ca, calcium; CAID, coefficient of apparent ileal digestibility; CSID, coefficient of standardized ileal digestibility; CP, crude protein; CATTD, coefficient of apparent total tract digestibility; CSTTD, coefficient of standardized total tract digestibility; DE, digestible energy; DM, dry matter; EPL, endogenous phosphorus loss; FTU, phytase units; GE, gross energy; ME, metabolizable energy; P, phosphorus.

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https://doi.org/10.1016/j.anifeedsci.2021.115040
Received 24 April 2021; Received in revised form 28 July 2021; Accepted 30 July 2021

1. Introduction

Corn is a cereal grain that is commonly used as a feed ingredient in diets for swine and poultry (Spencer et al., 2000), and corn can be grown under a wide range of environmental conditions (Rouf Shah et al., 2016). The continuing innovation and development of new corn genetics have resulted in creation of new cultivars that have greater nutritional value than conventional hybrids of corn. Indeed, hybrids with greater concentrations of oil have been developed and these high-oil corn hybrids have greater concentration of metabolizable energy (ME) than conventional yellow dent corn (Adeola and Bajjalieh, 1997; Pedersen et al., 2007). Dietary fat may increase amino acid (AA) digestibility by reducing gastric emptying and passage rate of ingested feed, which increases the time for proteases to act on feed protein (Kim et al., 2007; Cervantes-Pahm and Stein, 2008); therefore, high-oil corn hybrids may have greater digestibility of AA than conventional corn. A newly developed hybrid of high-oil corn has been developed by Byron Seeds LLC (Rockville, IN, USA), and it is possible that the new high-oil corn has greater digestibility of AA and energy than conventional hybrids, but this hypothesis has not been experimentally verified.

Inclusion of microbial phytase in diets for pigs usually improves digestibility of phosphorus (P) and increases P retention because phytase hydrolyzes the ester bond that binds P to the phytate molecule in corn and most other plant feed ingredients (Pallauf et al., 1994). However, there are at this point no data for effects of adding phytase to diets containing high-oil corn and no data to demonstrate digestibility of P in the newly developed high-oil corn have been published. It is also not known if the efficiency of phytase is different between conventional corn and high-oil corn. Therefore, 2 experiments were conducted to test the hypothesis that the coefficient of standardized ileal digestibility (CSID) of AA, coefficient of standardized total tract digestibility (CSTTD) of P, and concentrations of digestible energy (DE) and ME in a newly developed hybrid of high-oil corn are greater than in a conventional hybrid

Table 1
Analyzed composition of 2 sources of corn, as-fed basis.

Item	Conventional corn	High-oil corn
Dry matter, g/kg	866.0	885.0
Gross energy, MJ/kg	16.1	17.8
Starch, g/kg	613.1	516.8
Crude protein, g/kg	72.0	87.3
Acid-hydrolyzed ether extract, g/kg	45.2	89.8
Soluble dietary fiber, g/kg	10.0	ND[1]
Insoluble dietary fiber, g/kg	101.0	153.0
Total dietary fiber, g/kg	111.0	153.0
Ash, g/kg	14.1	14.0
Ca, g/kg	0.1	0.1
Total P, g/kg	2.8	3.9
Phytic acid, g/kg	7.2	8.2
Phytate-P[2], g/kg	2.0	2.3
Non-phytate P[3], g/kg	0.8	1.6
K, g/kg	4.0	3.0
Mg, g/kg	1.2	0.8
Na, mg/kg	36.1	39.7
Cu, mg/kg	3.6	2.4
Fe, mg/kg	35.1	25.2
Mn, mg/kg	9.4	6.6
Zn, mg/kg	27.4	23.0
Indispensable amino acids, g/kg		
Arg	3.2	4.4
His	1.9	2.5
Ile	2.8	3.5
Leu	8.4	10.6
Lys	2.2	3.2
Met	1.4	1.7
Phe	3.6	4.4
Thr	2.6	3.2
Trp	0.5	0.6
Val	3.4	4.7
Dispensable amino acids, g/kg		
Ala	5.3	6.9
Asp	5.1	6.4
Cys	1.6	1.8
Glu	13.2	16.4
Gly	2.9	3.7
Ser	3.3	4.0
Tyr	2.0	2.7
Lys:CP	3.06	3.67

[1] ND, not detected.

[2] Calculated as 282 g/kg phytic acid.

[3] Calculated as total P minus phytate P.

of corn when fed to growing pigs. The second objective was to test the hypotheses that inclusion of microbial phytase in diets improves the coefficient of apparent total tract digestibility (CATTD) and the CSTTD of P in high-oil corn, and that there are interactions between source of corn and phytase.

2. Materials and methods

Protocols for 2 experiments were submitted to the Institutional Animal Care and Use Committee at the University of Illinois, Urbana-Champaign, USA, and both protocols were approved prior to initiation of the experiments. Pigs used in both experiments were the offspring of Line 359 boars mated to Camborough females (Pig Improvement Company, Hendersonville, TN, USA). The newly developed high-oil corn was sourced from Byron Seeds LLC (Rockville, IN, USA; Table 1). Conventional corn was provided by a local supplier and sourced from the University of Illinois feed mill. The conventional corn and the high-oil corn used in the 2 experiments originated from the same batches.

2.1. Experimental design and sample collection

2.1.1. Experiment 1: amino acid digestibility

Three diets were formulated (Table 2). Two diets contained high-oil corn or conventional corn as the only source of crude protein (CP) and AA. A nitrogen-free diet that was used to determine the basal endogenous losses of AA from pigs was also prepared. Vitamins and minerals were included in all diets to meet or exceed current requirement estimates (NRC, 2012). All diets also contained 4.0 g/kg

Table 2
Composition of diets, experiment 1.

	Diet		
Ingredient, g/kg	Conventional corn	High-oil corn	N-free
Conventional corn	941.5	–	–
High-oil corn	–	941.5	–
Soybean oil	30.0	30.0	40.0
Solka floc[1]	–	–	40.0
Dicalcium phosphate	12.0	12.0	21.5
Ground limestone	7.0	7.0	4.5
Sucrose	–	–	200.0
Chromic oxide	4.0	4.0	4.0
Cornstarch	–	–	679.5
Magnesium oxide	–	–	1.0
Potassium carbonate	–	–	4.0
Salt	4.0	4.0	4.0
Vitamin-mineral premix[2]	1.5	1.5	1.5
Analyzed composition			
Dry matter, g/kg	860.3	873.2	919.2
Crude protein, g/kg	64.5	81.5	1.8
Indispensable amino acids, g/kg			
Arg	2.9	4.1	0.1
His	1.8	2.3	0.0
Ile	2.5	3.2	0.2
Leu	7.7	10.0	0.2
Lys	2.0	2.9	0.1
Met	1.2	1.5	0.0
Phe	3.3	4.3	0.1
Thr	2.3	3.0	0.1
Trp	0.5	0.5	0.1
Val	3.2	4.4	0.0
Dispensable amino acids, g/kg			
Ala	4.9	6.2	0.1
Asp	4.5	5.9	0.1
Cys	1.3	1.6	0.0
Glu	12.1	15.3	0.2
Gly	2.7	3.2	0.1
Ser	2.9	3.5	0.1
Tyr	2.0	2.6	0.1

[1] Fiber Sales and Development Corp., Urbana, OH, USA.

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

chromic oxide as an indigestible marker.

Nine gilts (initial body weight: 81.5 ± 5.9 kg) that had a T-cannula installed in the distal ileum (Stein et al., 1998) were allotted to a triplicated 3 × 3 Latin square design with 3 diets and three 7-day periods (Kim and Stein, 2009). Therefore, there were 9 replicate pigs per treatment. Pigs were placed in individual pens (1.5 × 2.5 m) in an environmentally controlled room. Each pen had smooth sides and partially slatted concrete floors. A nipple drinker and a feeder were also installed in each pen. All pigs were fed 3.2 times the maintenance energy requirement (i.e., 0.824 MJ per kg body weight$^{0.60}$; NRC, 2012) and water was available at all times. An AA mixture was provided to all pigs during the initial 5 days of each period, but not on days 6 and 7 (Table 3). Pig weights were recorded at the beginning of each period to calculate feed allowance during the following period.

The initial 5 days of each period was considered an adaptation period to the diet. Ileal digesta were collected for 9 h on days 6 and 7 using standard procedures. In short, a plastic bag was attached to the cannula barrel and digesta flowing into the bag were collected. Bags were removed when filled with ileal digesta, or at least once every 30 min, and immediately frozen at – 20 °C to prevent bacterial degradation of AA in the digesta. On the completion of one experimental period, animals were deprived of feed overnight, and the following morning, the new experimental diet was offered.

2.1.2. Experiment 2: energy and P digestibility

Sixty-four barrows (initial body weight: 18.8 ± 2.2 kg) were allotted to a randomized complete block design with 8 diets and 8 replicate pigs per diet. Pigs were assigned to treatment groups using a randomized complete block design with 2 blocks of 32 pigs and 4 replicate pigs per diet in each block. Weaning group was the blocking factor. Two diets based on each source of corn were formulated, and corn provided all energy and P in these diets (Table 4). Six additional diets were also formulated, and these diets were identical to the previous two diets with the exception that 500, 1000, or 2000 units of microbial phytase (FTU; Quantum Blue 5 G, AB Vista, Marlborough, UK) was added to each diet. Therefore, 8 diets were prepared. Other than P, vitamins and minerals were included in all diets to meet or exceed the estimated nutrient requirements for 11–25 kg pigs (NRC, 2012). Pigs were placed in individual metabolism crates that were equipped with a self-feeder, a nipple waterer and a slatted floor. A screen floor and a urine pan under the slatted floor allowed for quantitative collection of feces and urine. Pigs were fed at 3.2 times the energy requirement for maintenance, and pigs had free access to water throughout the experiment. Feed consumption was recorded daily. The initial 5 days was considered the adaptation period to the diet, whereas urine and fecal materials were collected during the following 4 days according to standard procedures using the marker-to-marker approach. Fecal collection was initiated when the first marker (i.e., chromic oxide) appeared in the feces and ceased when the second marker (i.e., ferric oxide) appeared (Adeola, 2001). Urine was collected in urine buckets over a preservative of 50 mL of hydrochloric acid. Fecal samples and subsamples of the collected urine were stored at -20 °C immediately after collection.

2.2. Chemical analyses

2.2.1. Experiment 1: amino acid digestibility

A sample of each source of corn and of each diet was collected at the time of diet mixing and used for chemical analysis. At the conclusion of experiment 1, ileal digesta samples were thawed and mixed within animal and diet, and a sub-sample was collected. Digesta samples were lyophilized and finely ground prior to chemical analysis. Ingredients, diets, and ileal digesta samples were analyzed for dry matter (DM; Method 930.15; AOAC Int., 2019). Samples of diets, ileal digesta, and ingredients were analyzed for nitrogen (Method 990.03; AOAC Int., 2019) on a LECO FP628 nitrogen analyzer (LECO Corp., Saint Joseph, MI, USA), and CP was calculated as nitrogen × 6.25. Diets, ileal digesta, and ingredients were also analyzed for AA using a Hitachi AA Analyzer (Model No. L8800; Hitachi High Technologies America, Inc., Pleasanton, CA, USA) with ninhydrin for postcolumn derivatization and norleucine as the internal standard. Diet and ileal digesta samples were analyzed for chromium (Method 990.08; AOAC Int., 2019). Acid-hydrolyzed ether extract (AEE) was analyzed in ingredients by acid hydrolysis using 3*N* HCl (AnkomHCl, Ankom Technology, Macedon, NY, USA) followed by crude fat extraction using petroleum ether (AnkomXT15, Ankom Technology, Macedon, NY, USA). The 2 sources of corn

Table 3
Composition of amino acid mixture, experiment 1[1].

Amino acid	g/kg
Gly	579.2
L-Lys HCl	135.1
DL-Met	44.4
L-Thr	57.9
L-Trp	13.5
L-Ile	42.5
L-Val	48.3
L-His	21.2
L-Phe	57.9
Total	1000.0

[1] One hundred grams of this mixture was fed daily to each pig during the adaptation periods.

Table 4
Composition of diets, experiment 2.

	Conventional corn				High-oil corn			
Ingredient, g/kg	0 FTU[1]/kg	500 FTU/kg	1000 FTU/kg	2000 FTU/kg	0 FTU/kg	500 FTU/kg	1000 FTU/kg	2000 FTU/kg
Conventional corn	984.7	984.7	984.7	984.7	–	–	–	–
High-oil corn	–	–	–	–	984.7	984.7	984.7	984.7
Cornstarch	0.8	0.7	0.6	0.4	0.8	0.7	0.6	0.4
Ground limestone	9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
Salt	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Phytase premix[2]	–	0.1	0.2	0.4	–	0.1	0.2	0.4
Vitamin-mineral premix[3]	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Analyzed values								
Dry matter, g/kg	865.3	864.1	866.9	860.0	883.1	881.4	882.8	884.4
Ash, g/kg	22.7	22.8	23.9	21.9	26.9	27.4	26.9	27.6
Gross energy, MJ/kg	15.7	15.7	15.7	15.7	17.6	17.6	17.6	17.6
Ca, g/kg	3.5	3.6	3.8	3.6	3.7	3.8	3.9	3.8
P, g/kg	2.9	2.7	2.6	2.8	3.5	3.7	3.7	3.8
Phytase, FTU/kg	<70	230	540	1200	<70	460	800	1400

[1] FTU = phytase units.

[2] The phytase premix (Quantum Blue 5000; AB Vista, Marlborough, UK) contained 5000 phytase units per gram. At 0.1 g/kg, 0.2 g/kg, and 0.4 g/kg inclusion, the premix provided 500, 1000, and 2000 units of phytase per kg in the complete diet, respectively.

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

were also analyzed for insoluble dietary fiber and soluble dietary fiber according to method 991.43 (AOAC Int., 2019) using the AnkomTDF Dietary Fiber Analyzer (Ankom Technology, Macedon, NY, USA). Total dietary fiber was calculated as the sum of insoluble dietary fiber and soluble dietary fiber.

2.2.2. Experiment 2: energy and P digestibility

At the conclusion of the experiment, urine samples were thawed and mixed within animal and diet, and a sub-sample was lyophilized before analysis. Fecal samples were thawed and mixed within pig and diet, and then dried in a 50 °C forced-air drying oven prior to analysis. Ingredients, diets, fecal, and urine samples were analyzed for gross energy (GE) using bomb calorimetry (Model 6400; Parr Instruments, Moline, IL, USA). Fecal, ingredient, and diet samples were also analyzed for DM as explained for experiment 1. These samples were also analyzed for ash (Method 942.05; AOAC Int., 2019) and for Ca and P using inductively coupled plasma optical emissions spectrometry (Avio 200, PerkinElmer, Waltham, MA, USA; Method 985.01 A, B, and C; AOAC Int., 2019). The 2 sources of corn were also analyzed for K, Mg, Na, Cu, Fe, Mn, and Zn using inductively coupled plasma optical emissions spectrometry. Diets were analyzed for phytase activity (Phytex Method, Version 1; Eurofins, Des Moines, IA, USA), and the 2 sources of corn were analyzed for phytic acid (Ellis et al., 1977). The concentration of phytate P in the 2 sources of corn was calculated by multiplying the analyzed concentration of phytic acid by 0.282 (Sauvant et al., 2004), and non-phytate P was calculated by subtracting the amount of phytate-P from total P. Starch was analyzed in corn sources using the glucoamylase procedure (Method 979.10; AOAC Int., 2019).

2.3. Calculations and statistical analyses

2.3.1. Experiment 1: amino acid digestibility

The coefficient of apparent ileal digestibility (CAID) and CSID of CP and AA in each source of corn were calculated (Stein et al., 2007). The basal endogenous losses of CP and AA were calculated from pigs fed the nitrogen-free diet as previously described (Stein et al., 2007). Data were analyzed using the MIXED procedure in SAS (SAS Institute Inc, 2016) with pig as the experimental unit. Homogeneity of the variances was verified and data were tested for outliers using the UNIVARIATE and BOXPLOT procedures, respectively. The model included corn source as main effect, whereas square, pig nested within square, and period were considered random effects. Least squares means were calculated using the LSmeans statement. Results were considered significant at $P \leq 0.05$ and considered a trend at $P \leq 0.10$.

2.3.2. Experiment 2: energy and P digestibility

Following analysis, the CATTD of GE and DM was calculated for each diet, and the DE and ME in each diet were calculated as well (NRC, 2012). The DE and ME of each source of corn were then calculated by dividing the DE and ME of the diet by the inclusion rate of corn in each diet. The CATTD of Ca and P in each diet was also calculated. By correcting the CATTD of P for the basal endogenous loss of P (i.e., 190 mg kg per DM intake; NRC, 2012), values for the CSTTD of P in each diet were calculated.

Data were analyzed in a 2 × 4 factorial arrangement using the MIXED procedure of SAS (SAS Institute Inc, 2016) with the pig as the experimental unit. Homogeneity of the variances was confirmed and data were tested for outliers as explained for experiment 1. For energy digestibility data, removed outliers included one pig fed each of the following diets: conventional corn diet with 500 FTU/kg phytase; high-oil corn diet with 1000 FTU/kg phytase; high-oil corn diet with 2000 FTU/kg. One pig for each dietary treatment except for the high-oil corn diet with 500 FTU/kg phytase was also identified as an outlier and removed from data for mineral digestibility. Orthogonal contrasts for a 2 × 4 factorial arrangement of treatments were used to determine linear, quadratic, and cubic effects of phytase, the main effect of corn, and corn × phytase interactions. Contrast statements were used with coefficients for unequally spaced treatments being generated using the Proc Interactive Matrix Language statement in SAS. Block and replicate within block were considered random effects. Treatment means were calculated using the LSMeans statement in SAS. Results were considered significant at $P \leq 0.05$ and considered a trend at $P \leq 0.10$.

3. Results

Concentrations of CP and AA in high-oil corn were greater than in conventional corn. The lysine concentration in high-oil corn and conventional corn was 3.2 g/kg and 2.2 g/kg, respectively. Conventional corn had greater concentration of starch (i.e., 613.1 g/kg) compared with high-oil corn (i.e., 516.8 g/kg), but high-oil corn contained 89.8 g/kg AEE compared with 45.2 g/kg AEE in conventional corn. The concentration of GE in high-oil corn and conventional corn was 17.8 and 16.1 MJ/kg, respectively. Concentration of phytate P was 2.3 and 2.0 g/kg in high-oil corn and in conventional corn, respectively. Total dietary fiber was 153 g/kg in high-oil corn and 111 g/kg in conventional corn.

3.1. *Amino acid digestibility*

Diet analyses indicated that the intended concentrations of CP and AA were present in all diets. All pigs remained healthy during the experimental period, and only little feed refusals were observed.

The CAID of CP and most AA was greater ($P < 0.05$) in high-oil corn than in conventional corn (Table 5). Likewise, the CSID of His, Ile, Leu, Lys, Phe, Thr, Val, Ala, Asp, Glu, and Tyr was greater ($P < 0.05$) in high-oil corn than in conventional corn. The CSID of CP, Arg, Met, Cys, and Ser also tended to be greater ($P < 0.10$) in high-oil corn than in conventional corn. The CAID and CSID of Trp were not different between the 2 sources of corn.

3.2. *Energy and P digestibility*

Diet analyses indicated that the intended nutrient concentrations were present in all diets. No interactions between corn source and phytase dose were observed for the CATTD of GE or concentrations of DE and ME in experimental diets (Table 6). The GE intake, fecal GE loss, and concentrations of DE and ME in diets were not affected by phytase supplementation. Pigs fed the high-oil corn diets had

Table 5

Coefficients of apparent ileal digestibility (CAID) and standardized ileal digestibility (CSID) of crude protein (CP) and amino acids (AA) in high-oil corn and in conventional corn, experiment 1[1,2].

	CAID				CSID			
Item	Conventional corn	High-oil corn[3]	SEM	P-value	Conventional corn	High-oil corn	SEM	P-value
CP	0.557	0.687	0.0404	0.005	0.828	0.904	0.0404	0.068
Indispensable AA								
Arg	0.688	0.807	0.0201	<0.001	0.950	0.995	0.0201	0.099
His	0.720	0.786	0.0157	0.002	0.812	0.859	0.0157	0.015
Ile	0.687	0.757	0.0192	0.002	0.796	0.843	0.0192	0.023
Leu	0.818	0.860	0.0111	0.003	0.872	0.902	0.0111	0.018
Lys	0.348	0.589	0.0527	<0.001	0.615	0.776	0.0527	0.005
Met	0.764	0.805	0.0150	0.014	0.823	0.852	0.0150	0.060
Phe	0.763	0.823	0.0141	0.001	0.838	0.882	0.0141	0.009
Thr	0.531	0.640	0.0285	0.001	0.735	0.799	0.0285	0.031
Trp	0.634	0.647	0.0329	0.715	0.793	0.809	0.0329	0.666
Val	0.683	0.767	0.0176	<0.001	0.792	0.848	0.0176	0.006
Dispensable AA								
Ala	0.747	0.808	0.0169	<0.001	0.866	0.903	0.0169	0.008
Asp	0.637	0.732	0.0193	<0.001	0.787	0.848	0.0193	0.006
Cys	0.613	0.684	0.0220	0.008	0.742	0.791	0.0220	0.053
Glu	0.798	0.852	0.0115	<0.001	0.865	0.905	0.0115	0.003
Gly	0.245	0.464	0.0902	0.037	0.862	0.992	0.0902	0.189
Ser	0.662	0.724	0.0179	0.004	0.826	0.863	0.0179	0.062
Tyr	0.695	0.772	0.0195	<0.001	0.802	0.855	0.0195	0.010

[1] Data are least squares means of 9 observations per treatment.

[2] Values for CSID were calculated by correcting the values for CAID for basal ileal endogenous losses. Basal ileal endogenous losses were determined (g/kg of DM intake) as CP, 20.27; Arg, 0.89; His, 0.19; Ile, 0.32; Leu, 0.48; Lys, 0.62; Met, 0.08; Phe, 0.29; Thr, 0.55; Trp, 0.09; Val, 0.41; Ala, 0.68; Asp, 0.78; Cys, 0.20; Glu, 0.94; Gly, 1.94; Ser, 0.55; and Tyr, 0.25.

Table 6

Coefficient of apparent total tract digestibility (CATTD) of gross energy (GE) and energy concentrations in experimental diets and in 2 sources of corn, experiment 2[1].

	Conventional corn				High-oil corn					P-values[2]			
Item	0 FTU[3]/kg	500 FTU/kg	1000 FTU/kg	2000 FTU/kg	0 FTU/kg	500 FTU/kg	1000 FTU/kg	2000 FTU/kg	SEM	Corn	Phytase, Linear	Phytase, Quadratic	Phytase, Cubic
Diets													
GE intake, MJ/day	12.94	12.14	13.05	12.22	14.25	14.89	13.50	14.23	0.552	<0.001	0.378	0.797	0.796
GE in feces, MJ/day	1.39	1.47	1.50	1.40	1.69	1.79	1.58	1.73	0.157	<0.001	0.951	0.734	0.232
GE in urine, MJ/day	0.22	0.23	0.20	0.22	0.25	0.23	0.25	0.26	0.042	0.083	0.935	0.607	0.793
CATTD of GE	0.893	0.879	0.886	0.886	0.881	0.878	0.883	0.879	0.012	0.100	0.719	0.557	0.148
DE[4], MJ/kg	14.06	13.84	13.95	13.95	15.52	15.46	15.54	15.48	0.201	<0.001	0.644	0.438	0.161
ME[4], MJ/kg	13.79	13.61	13.72	13.67	15.22	15.19	15.22	15.66	0.177	<0.001	0.494	0.791	0.321
Ingredients													
As-fed basis													
DE, MJ/kg	14.28	14.05	14.16	14.16	15.77	15.70	15.78	15.72	0.204	<0.001	0.644	0.438	0.161
ME, MJ/kg	14.00	13.82	13.94	13.88	15.46	15.43	15.46	15.40	0.180	<0.001	0.494	0.791	0.321
Dry matter basis													
DE, MJ/kg	16.48	16.23	16.37	16.36	17.81	17.75	17.83	17.77	0.233	<0.001	0.643	0.432	0.158
ME, MJ/kg	16.17	15.96	16.09	16.03	17.47	17.44	17.47	17.40	0.206	<0.001	0.493	0.787	0.317

[1] Data are least squares means of 8 observations per treatment, except for conventional corn diet with 500 FTU/kg phytase, high-oil corn diet with 1000 FTU/kg phytase, and high-oil corn diet with 2000 FTU/kg, which represent 7 observations per treatment.

[2] Corn × phytase effects were not significant, therefore, only main effects of corn and phytase (orthogonal polynomial contrasts) were indicated.

[3] FTU, phytase units.

[4] DE, digestible energy; ME, metabolizable energy.

greater ($P < 0.001$) GE intake and fecal excretion of GE compared with pigs fed the conventional corn diets. Likewise, pigs fed the high-oil corn diets tended to have greater ($P = 0.083$) urine excretion of GE compared with pigs fed the conventional corn diets. The CATTD of GE was not different between diets containing high-oil corn and diets containing conventional corn. However, because of the greater GE in the high-oil corn diets compared with the diets based on conventional corn, concentrations of DE and ME in high-oil corn diets were greater ($P < 0.001$) than in conventional corn diets. As a result, concentrations of DE and ME in high-oil corn were greater ($P < 0.001$) than in conventional corn.

Neither the source of corn nor phytase influenced daily feed intake or daily basal endogenous P loss (Table 7). Inclusion of 500 FTU/kg of phytase in the conventional corn diet reduced the daily P intake of pigs compared with pigs fed the conventional corn diet without phytase; however, pigs fed the high-oil corn diet with 500 FTU/kg of phytase had greater daily P intake than pigs fed diets without phytase (cubic interaction, $P = 0.014$). Pigs fed diets containing 500, 1000, or 2000 FTU/kg of phytase had reduced (linear and quadratic, $P < 0.001$; cubic, $P = 0.008$) concentration of P in feces compared with pigs fed diets without phytase, but no difference between the 2 corn hybrids were observed for concentration of P in feces. The quantity of P excreted in feces was reduced (linear and quadratic, $P < 0.001$) when phytase was added to the diets, and pigs fed diets based on high-oil corn had less ($P = 0.01$) excretion of P than pigs fed diets based on conventional corn. As a result, diets containing phytase had greater (linear and quadratic, $P < 0.001$) CATTD and CSTTD of P than diets without phytase. When phytase was included in the diets, absorption of P was greater for pigs fed diets based on high-oil corn than pigs fed diets containing conventional corn (cubic interaction, $P = 0.008$). Therefore, CATTD and CSTTD of P were greater ($P < 0.001$) in high-oil corn than in conventional corn.

Inclusion of 500 FTU/kg of phytase in the conventional corn diet reduced the daily Ca intake of pigs; however, phytase did not affect the daily Ca intake of pigs fed the high-oil corn diets (Table 8; cubic interaction, $P = 0.003$). Pigs fed diets containing 500, 1000 or 2000 FTU/kg of phytase had reduced (linear and quadratic, $P < 0.001$; cubic, $P = 0.005$) excretion of Ca in feces compared with pigs fed diets without phytase. As a result, Ca absorption was increased (linear and quadratic, $P < 0.001$) if phytase was added to the diets regardless of source of corn. Diets containing phytase also had greater (linear and quadratic, $P < 0.001$) CATTD of Ca than diets without phytase, but there was no effect of source of corn on CATTD of Ca.

4. Discussion

Corn is the main source of energy in diets fed to pigs in the United States and in many other countries around the world (Pedersen et al., 2007). Although highly palatable and high in starch, varieties with increased concentrations of CP and oil have been developed to increase the nutritional value of corn (Daghir et al., 2003; Pedersen et al., 2007). The observation that high-oil corn had greater concentrations of CP, AEE, and total P than conventional corn indicates that the breeding technology used to produce the high-oil corn used in this experiment was effective in increasing protein, oil, and mineral concentrations.

Table 7

Effects of microbial phytase on phosphorus (P) balance, coefficient of apparent total tract digestibility (CATTD), and coefficient of standardized total tract digestibility (CSTTD) of P in conventional corn and high-oil corn fed to growing pigs, experiment 2[1].

Item	Feed intake, g/day	P intake, g/day	P in feces, g/kg	P output, g/day	P absorption, g/day	CATTD of P	Basal EPL[2], mg/day	CSTTD of P[3]
Conventional corn								
0 FTU[4]/kg	818	2.38	17.00	1.34	1.03	0.427	134	0.484
500 FTU/kg	770	2.08	11.54	0.94	1.15	0.549	126	0.610
1000 FTU/kg	839	2.18	9.73	0.60	1.59	0.720	138	0.784
2000 FTU/kg	783	2.19	7.39	0.58	1.62	0.730	128	0.788
High-oil corn								
0 FTU/kg	808	2.84	17.33	1.36	1.49	0.521	136	0.569
500 FTU/kg	846	3.13	10.82	0.73	2.40	0.762	142	0.806
1000 FTU/kg	780	2.89	8.74	0.48	2.41	0.834	131	0.879
2000 FTU/kg	810	3.09	6.73	0.45	2.65	0.855	136	0.899
SEM	35.795	0.115	0.513	0.056	0.124	0.027	5.939	0.027
P-values								
Corn	0.690	<0.001	0.173	0.010	<0.001	<0.001	0.223	<0.001
Phytase, Linear	0.588	0.784	<0.001	<0.001	<0.001	<0.001	0.554	<0.001
Phytase, Quadratic	0.891	0.401	<0.001	<0.001	0.001	<0.001	0.873	<0.001
Phytase, Cubic	0.858	0.567	0.008	0.879	0.519	0.792	0.813	0.763
Corn × Phytase, Linear	0.962	0.142	0.416	0.370	0.108	0.896	0.877	0.830
Corn × Phytase, Quadratic	0.655	0.218	0.289	0.199	0.122	0.328	0.593	0.409
Corn × Phytase, Cubic	0.125	0.014	0.842	0.141	0.008	0.134	0.124	0.135

[1] Data are least squares means of 7 observations per treatment, except for the high-oil corn diet with 500 FTU/kg phytase which represent 8 observations per treatment.

[2] EPL, endogenous phosphorus loss. This value was estimated to be at 190 mg/kg dry matter (DM) intake. The daily basal EPL (mg/day) for each diet was calculated by multiplying the EPL (mg/kg DM intake) by the daily DM intake of each diet.

[3] Values for CSTTD were calculated by correcting values for CATTD for the basal endogenous loss of phosphorus.

[4] FTU = phytase units.

Table 8
Effects of microbial phytase on calcium (Ca) balance and coefficient of apparent total tract digestibility (CATTD) of Ca in conventional corn and high-oil corn fed to growing pigs, experiment 2[1].

Item	Ca intake, g/day	Ca in feces, g/kg	Ca output, g/day	Ca absorption, g/day	CATTD of Ca
Conventional corn					
0 FTU[2]/kg	2.86	10.57	0.84	2.02	0.705
500 FTU/kg	2.77	6.40	0.52	2.26	0.813
1000 FTU/kg	3.19	5.25	0.33	2.86	0.895
2000 FTU/kg	2.82	4.16	0.33	2.49	0.883
High-oil corn					
0 FTU/kg	2.83	11.38	0.90	1.95	0.687
500 FTU/kg	3.13	6.05	0.40	2.72	0.868
1000 FTU/kg	2.89	5.91	0.32	2.57	0.889
2000 FTU/kg	3.08	4.14	0.28	2.81	0.911
SEM	0.130	0.655	0.054	0.122	0.018
P-values					
Corn	0.364	0.497	0.407	0.165	0.230
Phytase, Linear	0.363	<0.001	<0.001	<0.001	<0.001
Phytase, Quadratic	0.135	<0.001	<0.001	<0.001	<0.001
Phytase, Cubic	0.787	0.005	0.198	0.676	0.147
Corn × Phytase, Linear	0.491	0.666	0.507	0.338	0.465
Corn × Phytase, Quadratic	0.297	0.870	0.481	0.411	0.590
Corn × Phytase, Cubic	0.003	0.275	0.160	0.001	0.128

[1] Data are least squares means of 7 observations per treatment, except for the high-oil corn diet with 500 FTU/kg phytase, which had 8 observations per treatment.

[2] FTU = phytase units.

The analyzed concentrations of CP, AEE, and GE in conventional corn used in this experiment are in agreement with published values (Sauvant et al., 2004; NRC, 2012; Thomas et al., 2020). The analyzed values for ash, Ca, and total P in conventional corn are also in agreement with previous data (Selle et al., 2003; NRC, 2012; Li et al., 2014; Thomas et al., 2020). The analyzed concentrations of CP and AEE in the newly developed high-oil corn that was used in the experiment concur with values reported by Adeola and Bajjalieh (1997) and Benitez et al. (1999) for other hybrids of high-oil corn.

4.1. Amino acid digestibility

The observation that values for CSID of AA in high-oil corn were greater than in conventional corn may be a result of an increased proportion of germ protein and increased concentration of intact fat in high-oil corn (Li and Sauer, 1994; Parsons et al., 1998). Dietary fat may increase AA digestibility by increasing the retention time of the ingested feed, and this provides more time for AA digestion and absorption (Zhao et al., 2000; Kim et al., 2007; Cervantes-Pahm and Stein, 2008). Similar results were reported by Pedersen et al. (2007) and Song et al. (2003) who demonstrated that high-oil corn hybrids had greater digestibility of AA than conventional corn. Most CSID values for AA obtained in the 2 sources of corn are in agreement with reported data (Pedersen et al., 2007; NRC, 2012). However, the CSID values for lysine in this experiment were less compared with values reported by NRC (2012). Heat is applied during drying of corn and excessive heat may reduce digestibility and concentrations of AA due to formation of Maillard reaction products (Pahm et al., 2008; González-Vega et al., 2011). However, the Lysine to CP ratio in conventional corn and high-oil corn was 3.06 and 3.67 %, respectively, which indicates that the 2 corn sources were not heat damaged. Therefore, the observed reduction in the CSID of lysine in corn sources is likely not a result of heat damage, but possibly due to other processing conditions. Natural differences in digestibility among corn varieties may also exist (Pedersen et al., 2007; Li et al., 2014).

4.2. Energy and P digestibility

Values for GE and CATTD of GE in conventional corn used in the experiment are in agreement with reported data (NRC, 2012; Espinosa and Stein, 2018). Likewise, the calculated DE and ME for conventional corn are in close agreement with previous data (Sauvant et al., 2004; NRC, 2012; Thomas et al., 2020). The observation that high-oil corn had greater DE and ME than conventional corn is likely a result of increased concentrations of protein and fat in high-oil corn, and this is also consistent with previous data (Pedersen et al., 2007). The observation that phytase did not influence the CATTD of GE or concentrations of DE and ME in the 2 sources of corn are in agreement with data indicating that adding 250 to 3000 FTU/kg of phytase to a corn-based diet did not affect energy digestibility (Adeola et al., 2004; Lu et al., 2019).

The observed interaction between corn and phytase on Ca and P intake was unexpected because phytase did not impact feed intake of pigs. However, there were more orts from pigs fed the conventional corn diet with 500 FTU/kg compared with the high oil corn diet, which subsequently influenced Ca and P intake. Values for CSTTD of P are more additive in mixed diets compared with values for CATTD of P (She et al., 2018), and values for CSTTD are determined by correcting CATTD values for the basal endogenous loss of P (Almeida and Stein, 2010; NRC, 2012). Values for the basal endogenous loss of P that are estimated using a P-free diet are relatively constant regardless of body weight of pigs and an average of a number of experiments indicated that a value of 190 mg/kg of DM intake is representative of the basal endogenous loss of P (NRC, 2012). The CSTTD of P in conventional corn without phytase was slightly greater than published data (Almeida and Stein, 2010; NRC, 2012; Rojas et al., 2013), which is likely due to the presence of more nonphytate P in the conventional corn used in this experiment compared with previously used sources of corn. However, the CSTTD of P in the conventional corn used in this experiment is in agreement with data by Thomas et al. (2020). The observed increase in the CATTD and CSTTD of P in both hybrids of corn upon phytase supplementation indicates that the exogenous phytase hydrolyzed some of the ester bonds between P and the inositol ring of phytate, which resulted in increased absorption of P (Adeola et al., 1995). The observed increase in the digestibility of P in diets containing phytase is in agreement with published data (Poulsen et al., 2010; Blavi et al., 2017; Arredondo et al., 2019). The observation that P absorption was greater in pigs fed the high-oil corn diets compared with pigs fed the conventional corn diets when phytase was added to diets indicates that the efficiency of phytase in increasing P digestibility is greater in high-oil corn than in conventional corn. It is possible that phytate in high-oil corn is more accessible to phytase compared with phytate in conventional corn, but further research is needed to confirm this. The observation that high-oil corn had greater CSTTD of P than conventional corn is also likely a result of the calculated increased concentration of non-phytate P in high-oil corn.

All diets contained 9.0 g/kg calcium carbonate, and due to the low concentration of Ca in conventional corn and high-oil corn, the CATTD of Ca in the diets primarily reflects the CATTD of Ca in calcium carbonate. The calculated values for the CATTD of Ca in calcium carbonate in this experiment is in agreement with values reported by Lee et al. (2019). The observed improvement in Ca digestibility in diets containing high-oil corn or conventional corn indicates that phytase was also effective in hydrolyzing the Ca-phytate complexes in the gastrointestinal tract of pigs (Selle et al., 2009). This observation is in agreement with data indicating that the CATTD of Ca from calcium carbonate increased as phytase was added to the diets (Guggenbuhl et al., 2007; González-Vega et al., 2015). Thus, adding phytase to diets for pigs increases not only the digestibility of P, but also the digestibility of Ca.

5. Conclusion

High-oil corn contained more standardized ileal digestible amino acids, digestible energy, and metabolizable energy compared with conventional corn. Addition of 500 to 2000 units per kg of microbial phytase increased P digestibility in both hybrids of corn, but the standardized total tract digestibility of P in high oil corn, regardless of phytase supplementation, was greater than in conventional corn. These results indicate that high-oil corn can be used as an alternative for other cereal grains in diets for pigs, and that high-oil corn has a greater nutritional value than conventional corn.

Author statement

CDE and HHS conceptualized the experiment. NSF conducted the animal part of the experiment and summarized and analyzed data. CDE and HHS contributed with data interpretation. CDE wrote the first draft of the manuscript. NSF and HHS edited the final version of the manuscript. HHS supervised the project.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgements

The authors appreciate the financial support for this research from Byron Seeds, LLC, Rockville, IN, USA.

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