Phosphorus digestibility and concentration of digestible and metabolizable energy in corn, corn coproducts, and bakery meal fed to growing pigs

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Phosphorus digestibility and concentration of digestible and metabolizable energy in corn, corn coproducts, and bakery meal fed to growing pigs[1]

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ABSTRACT: Two experiments were conducted to determine the standardized total tract digestibility (STTD) of P and the concentration of DE and ME in corn, hominy feed, bakery meal, distillers dried grains with solubles (DDGS), corn gluten meal, corn gluten feed, and corn germ meal fed to growing pigs. In Exp. 1, 84 barrows (initial BW: 13.7 ± 2.3 kg) were placed in metabolism cages and allotted to 14 diets with 6 replicate pigs per diet in a randomized complete block design. Seven diets were formulated to contain corn, hominy feed, bakery meal, DDGS, corn gluten meal, corn gluten feed, or corn germ meal as the sole source of P. Seven additional diets were similar to the initial 7 diets with the exception that 600 units of microbial phytase was included in each diet. The STTD of P was greater ($P < 0.05$) in DDGS, corn gluten meal, and corn gluten feed than in corn, hominy feed, bakery meal, and corn germ meal, and the STTD of P was also greater ($P < 0.05$) in bakery meal than in corn and hominy feed. Addition of phytase increased ($P < 0.05$) the STTD of P in corn, hominy feed, bakery meal, and corn germ meal but not in corn gluten meal, corn gluten feed, or DDGS. In Exp. 2, 56 barrows (initial BW: 14.6 ± 2.2 kg) were placed in metabolism cages and allotted to 7 diets with 8 replicate pigs per diet in a randomized complete block design. A corn-based diet consisting of 97.5% corn and vitamins and minerals was formulated. Four additional diets were formulated by mixing corn and DDGS, corn gluten feed, corn gluten meal, or corn germ meal, and 2 diets were based on hominy feed or bakery meal. The concentration of ME was 3,891, 3,675, 3,655, 3,694, 4,400, 3,169, and 3,150 kcal/kg DM in corn, hominy feed, bakery meal, DDGS, corn gluten meal, corn gluten feed, and corn germ meal, respectively. The ME (DM basis) in corn was greater ($P < 0.05$) than in hominy feed, bakery meal, corn gluten feed, and corn germ meal, but less ($P < 0.05$) than in corn gluten meal, and the ME in hominy feed, bakery meal, and DDGS was greater ($P < 0.05$) than in corn gluten feed and corn germ meal. In conclusion, DDGS, corn gluten meal, and corn gluten feed have a greater STTD of P than corn, hominy feed, bakery meal, and corn germ meal, but phytase can be included in diets containing corn, hominy feed, bakery meal, and corn germ meal to improve P digestibility. The ME in corn gluten meal is greater than in bakery meal, corn, and other corn coproducts.

Key words: bakery meal, corn, corn coproducts, energy, phosphorus digestibility, pig

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INTRODUCTION

Many coproducts from the human food industry may be used in diets fed to pigs and poultry. Such ingredients include hominy feed, bakery meal, corn gluten meal, corn gluten feed, and corn germ meal and effects of some of these ingredients on pig growth performance have been reported (Mahan and Newton, 1993; Kwak and Kang, 2006). The apparent and standardized ileal digestibility of CP and AA in hominy feed, bakery meal, corn gluten meal, corn gluten feed, and corn germ meal have also been reported (Almeida et al., 2011). However, there is a lack of data for the DE and ME in these ingredients and there are no comparative data for the DE and ME in these ingredients and corn and distillers dried grains with solubles (**DDGS**).

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Much of the P in plant ingredients is bound to phytate (Eeckhout and De Paepe, 1994), which decreases P digestibility. However, addition of microbial phytase to corn and soybean meal (**SBM**) increases P digestibility, but that is not always the case when microbial phytase is added to DDGS (Almeida and Stein, 2010, 2012) because fermentation reduces the concentration of phytate in feed ingredients (Almeida and Stein, 2010; Rojas and Stein, 2012). There are, however, no data on the effect of microbial phytase when added to corn gluten meal, corn gluten feed, corn germ meal, hominy feed, and bakery meal, and there are no comparative data for P digestibility among these ingredients. Therefore, the first objective of this work was to determine the standardized total tract digestibility (**STTD**) of P and the effect of microbial phytase on the STTD of P in hominy feed, bakery meal, corn gluten meal, corn gluten feed, and corn germ meal. The second objective was to determine the concentration of DE and ME in these ingredients and to compare these values with values obtained for corn and DDGS.

MATERIALS AND METHODS

Two experiments were conducted, and the Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocols for both experiments.

Pigs with the same genetic background were used in both experiments (G-performer boars × Fertilium 25 females; Genetiporc, Alexandria, MN). Ingredients used in the experiments included corn, hominy feed, bakery meal, DDGS, corn gluten meal, corn gluten feed, and corn germ meal (Table 1). The same batches of these ingredients were used in both experiments. The hominy feed, the bakery meal, and the DDGS were sourced from Archer Daniels Midland (Decatur, IL). Corn gluten meal, corn gluten feed, and corn germ meal were sourced from Agricolor Inc. (Marion, IN), Custom Trading and Blending (Terra Haute, IN), and Big Rivers Resources (West Burlington, IA), respectively. The corn was a commercial hybrid of yellow dent corn that was sourced from the University of Illinois Feed Mill (Champaign, IL).

Phosphorus Digestibility (Experiment 1)

Diets, Animals, and Experimental Design. Experiment 1 was designed to determine apparent total tract digestibility (**ATTD**) and STTD of P in hominy feed, bakery meal, corn gluten meal, corn gluten feed, and corn germ meal and to compare these values to the values obtained for corn and DDGS. Eighty-four barrows (initial BW: 13.7 ± 2.3 kg) were placed in metabolism cages in a randomized complete block design with 14 diets and 6 replicate pigs per diet. Three diets were based on corn, hominy feed, or bakery meal and no inorganic P was included in these diets (Table 2). Four additional diets were formulated by mixing cornstarch and sugar with corn gluten meal, corn gluten feed, corn germ meal, or DDGS and the corn coproducts were the sole sources of P in these diets. Seven additional diets that were similar to the initial 7 diets with the exception that 600 units per kilogram of microbial phytase (Optiphos 2000; Enzyvia, Sheridan, IN) were added to each diet were also formulated. Vitamins and all minerals except P were included in the diets according to requirements (NRC, 1998).

Feeding and Sample Collection. Feed was supplied in a daily amount of 2.5 times the maintenance energy requirement (i.e., 106 kcal of ME/kg of $BW^{0.75}$; NRC, 1998) of the smallest pig in each replicate and divided into 2 equal meals that were fed at 0800 and 1700 h. Water was available at all times. Pigs were fed experimental diets for 12 d. The initial 5 d were considered an adaptation period to the diet. Fecal markers were fed on d 6 (chromic oxide) and d 11 (ferric oxide) and fecal collections were initiated when chromic oxide appeared in the feces and ceased when ferric oxide appeared (Adeola, 2001). Feces were collected twice daily and stored at –20°C immediately after collection.

Chemical Analyses. All samples were analyzed in duplicate. Fecal samples were dried at 65°C in a forced-air oven and ground through a 1-mm screen in a Wiley mill (Model 4; Thomas Scientific, Swedesboro, NJ) before analysis. Diets, ingredients, and fecal samples were analyzed for DM (method 930.15; AOAC, 2007), and P and Ca were analyzed in all samples by the inductively coupled plasma spectroscopy procedure (method 985.01 A, B, and C; AOAC, 2007) after wet ash sample preparation [method 975.03 B(b); AOAC, 2007]. Diets and ingredients were also analyzed for ash (method 942.05; AOAC, 2007), phytase activity (Phytex Method, version 1; Eurofins, Des Moines, IA), and phytate concentration (Ellis et al., 1977). All ingredients were analyzed for GE by adiabatic bomb calorimetry (Model 6300 Parr Instruments, Moline, IL), ADF (method 973.18; AOAC, 2007), and NDF (Holst, 1973), and AA were analyzed in the ingredients (Hitachi Amino Acid Analyzer, Model 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, 2007]. Crude protein was analyzed in all ingredients by combustion (method 990.03; AOAC, 2007) using an apparatus (Elementar Rapid N-cube Protein/Nitrogen Apparatus; Elementar Americas Inc., Mt. Laurel, NJ). Acid hydrolyzed ether extract (**AEE**) was determined by acid hydrolysis using 3 *N* HCl (Sanderson, 1986) followed by crude fat extraction using petroleum ether (method 2003.06; AOAC, 2007) on an automated analyzer (Soxtec 2050; FOSS North America,

Table 1. Analyzed nutrient composition of corn, hominy feed, bakery meal, distillers dried grains with solubles (DDGS), corn gluten meal, corn gluten feed, and corn germ meal (as-fed basis)

	Ingredient						
Item	Corn	Hominy feed	Bakery meal	DDGS	Corn gluten meal	Corn gluten feed	Corn germ meal
GE, kcal/kg	3,924	4,407	4,098	4,769	5,102	4,324	4,184
DM, %	86.74	89.01	88.44	87.55	91.03	85.87	89.41
CP, %	6.68	9.41	8.05	25.43	62.88	23.00	24.76
AEE,[1] %	3.40	9.47	7.12	10.36	4.29	4.15	2.06
Ash, %	1.06	3.12	7.31	5.07	3.16	5.71	5.47
Ca, %	0.01	0.01	0.20	0.22	0.01	0.12	0.18
P, %	0.19	0.70	0.48	0.82	0.57	0.87	0.87
Phytate, %	0.55	2.07	0.78	0.43	1.69	0.71	2.06
Phytate-bound P,[2] %	0.16	0.58	0.22	0.12	0.48	0.20	0.58
Phytate-bound P, % of total P	81.63	83.39	45.83	14.79	83.61	23.01	66.77
Nonphytate P,[3] %	0.03	0.12	0.26	0.70	0.09	0.67	0.29
Nonphytate-bound P, % of total P	18.37	16.61	54.18	85.21	16.39	76.99	33.23
Phytase, phytase unit/kg	<100	130	330	260	280	340	100
Carbohydrates, %							
Glucose	0.66	1.53	5.03	1.84	0.26	0.37	0.26
Sucrose	1.14	1.93	4.91	0.19	0.14	0.11	0.35
Maltose	0.23	0.57	2.85	2.28	0.15	1.86	0.72
Fructose	0.40	1.32	4.71	0.74	0.50	0.38	0.55
Starch, %	67.29	35.63	38.53	4.56	6.68	9.77	15.93
NDF, %	8.53	21.79	8.19	35.20	10.45	30.88	49.29
ADF, %	2.00	5.51	3.06	10.02	5.23	7.68	11.30
Indispensable AA, %							
Arg	0.33	0.66	0.45	1.13	2.26	0.95	1.55
His	0.19	0.28	0.20	0.67	1.31	0.61	0.64
Ile	0.23	0.32	0.31	0.92	2.60	0.79	0.84
Leu	0.76	0.87	0.65	2.75	10.09	1.86	1.86
Lys	0.22	0.48	0.25	0.75	1.18	1.02	0.94
Met	0.14	0.19	0.12	0.48	1.61	0.32	0.40
Phe	0.31	0.41	0.37	1.24	4.03	0.87	1.04
Thr	0.24	0.37	0.25	0.97	2.03	1.21	0.83
Trp	0.04	0.03	0.08	0.19	0.44	0.16	0.18
Val	0.32	0.48	0.41	1.33	2.89	1.12	1.30
Dispensable AA, %							
Ala	0.47	0.65	0.40	1.62	5.30	1.48	1.38
Asp	0.44	0.73	0.53	1.60	3.85	1.44	1.68
Cys	0.15	0.22	0.16	0.50	1.14	0.43	0.33
Glu	1.13	1.43	1.83	3.04	12.04	2.70	2.84
Gly	0.27	0.49	0.37	0.99	1.84	1.03	1.23
Pro	0.31	0.73	0.63	1.75	5.68	1.61	1.09
Ser	0.30	0.41	0.31	1.07	2.54	0.73	0.80
Tyr	0.21	0.28	0.23	0.91	3.27	0.64	0.67
Total AA	6.06	9.03	7.55	21.91	64.1	18.97	19.6

[1]AEE = acid hydrolyzed ether extract.

[2]Phytate-bound P was calculated as 28.2% of phytate (Tran and Sauvant, 2004).

[3]Nonphytate P was calculated as the difference between total P and phytate-bound P.

Eden Prairie, MN). Ingredients were also analyzed for total starch using the glucoamylase procedure (method 979.10; AOAC, 2007), and monosaccharides were analyzed as described by Cervantes-Pahm and Stein (2010).

Calculations and Statistical Analysis. The ATTD of P was calculated for each ingredient using the direct procedure (Almeida and Stein, 2010). The STTD of P was calculated for each ingredient by correcting the ATTD of P for the endogenous P loss, which was assumed to be 200 mg/kg DMI (Stein, 2011). The concentration of nonphytate- and phytate-bound P in corn and coproducts were calculated as previously described (Rojas and Stein, 2012).

Data were analyzed using the MIXED Procedure (SAS Inst. Inc., Cary, NC). Homogeneity of the variances among treatments was confirmed using the UNIVARIATE procedure and this procedure was also used to test for outliers, but no outliers were identified. The fixed effects were diet, phytase, and their interaction and block and

Table 2. Composition of experimental diets without and with phytase[1] containing corn, hominy feed, bakery meal, distillers dried grains with solubles (DDGS), corn gluten meal, corn gluten feed, or corn germ meal (as-fed basis), Exp. 1

	Diet						
Item	Corn	Hominy feed	Bakery meal	DDGS	Corn gluten meal	Corn gluten feed	Corn germ meal
Ingredients, %							
Ground corn	98.57	–	–	–	–	–	–
Coproduct	–	98.17	98.37	50.00	30.00	50.00	50.00
Cornstarch	0.03	0.03	0.03	38.20	58.80	38.40	38.40
Sucrose	–	–	–	10.00	10.00	10.00	10.00
Ground limestone	0.70	1.10	0.90	1.10	0.50	0.90	0.90
Sodium chloride	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin mineral premix[2]	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Analyzed composition							
Diet without microbial phytase							
DM, %	89.07	89.97	87.70	89.78	93.04	89.33	92.09
Ca, %	0.29	0.61	0.54	0.57	0.27	0.49	0.51
P, %	0.29	0.69	0.48	0.42	0.20	0.45	0.44
Ash, %	2.71	4.52	7.85	3.96	2.08	4.62	3.61
Phytate, %	0.77	2.19	0.84	0.21	0.54	0.36	1.06
Phytase, phytase units/kg	210	130	350	170	170	<100	<100
Diet with microbial phytase							
DM, %	87.58	89.88	87.19	91.02	93.57	90.09	92.79
Ca, %	0.32	0.52	0.55	0.59	0.26	0.52	0.65
P, %	0.22	0.70	0.48	0.42	0.19	0.46	0.48
Ash, %	2.34	3.28	8.60	4.39	1.44	3.97	3.61
Phytate, %	0.58	2.13	0.85	0.19	0.53	0.37	1.02
Phytase, phytase units/kg	560	840	1,200	870	740	810	860

[1]Microbial phytase was included at 0.03% in all diets at the expense of cornstarch [2000 phytase (Optiphos 2000; Enzyvia, Sheridan, IN) units/g].

[2]Provided the following quantities of vitamins and microminerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,128 IU; vitamin D_3 as cholecalciferol, 2,204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.58 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 as nicotinamide and nicotinic acid, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate; Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

replicate were considered random effects. The LSMeans statement was used to calculate treatment means, and the PDIFF option was used to separate means if differences were detected. The pig was the experimental unit for all analyses and an α level of 0.05 was used to assess significance among means.

Energy Digestibility (Experiment 2)

Diets, Animals, and Experimental Design. Experiment 2 was designed to determine ATTD of GE and the concentration of DE and ME in corn, hominy feed, bakery meal, DDGS, corn gluten meal, corn gluten feed, and corn germ meal. Fifty-six barrows (initial BW: 14.6 ± 2.2 kg) were placed in metabolism cages equipped with a feeder and a nipple drinker in a randomized complete block design with 7 diets and 8 replicate pigs per diet. A corn-based diet and 4 diets containing corn and DDGS, corn gluten feed, corn gluten meal, or corn germ meal were formulated (Table 3). Two additional diets that contained hominy feed or bakery meal as the only source of energy were also formulated. Vitamins and minerals were included in the diets to meet or exceed the requirements for weanling pigs (NRC, 1998).

Feeding and Sample Collection. Feed was supplied in a daily amount of 3 times the maintenance energy requirement (i.e., 106 kcal of ME/kg of $BW^{0.75}$; NRC, 1998) of the smallest pig in each replicate and divided into 2 equal meals that were provided at 0800 and 1700 h. Water was available at all times. Pigs were fed experimental diets for 12 d. Feces were collected twice daily as explained for Exp. 1 and stored at –20°C immediately after collection. Urine collections were initiated on d 6 at 1700 h and ceased on d 11 at 1700 h. Urine buckets were placed under the metabolism cages to permit total collection and buckets were emptied in the morning and afternoon and a preservative of 50 mL of sulfuric acid was added to each bucket when they were emptied. The collected urine was weighed and a 10% subsample was stored at –20°C.

Chemical Analysis. Fecal samples were dried and ground at the conclusion of the experiment as described for Exp. 1. Urine samples were thawed and mixed within animal and diet, and a subsample was lyophilized before energy analysis as previously described (Kim et al.,

Table 3. Composition of experimental diets containing corn, hominy feed, bakery meal, distillers dried grains with solubles (DDGS), corn gluten meal, corn gluten feed, or corn germ meal (as-fed basis), Exp. 2

	Diet						
Item	Corn	Hominy feed	Bakery meal	DDGS	Corn gluten meal	Corn gluten feed	Corn germ meal
Ingredient, %							
Ground corn	97.50	–	–	47.70	77.60	48.00	47.90
Coproduct	–	97.90	97.70	50.00	20.00	50.00	50.00
Ground limestone	0.70	1.10	0.90	1.60	0.80	1.30	1.20
Dicalcium phosphate	1.10	0.30	0.70	–	0.90	–	0.20
Sodium chloride	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin–mineral premix[1]	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Analyzed composition							
GE, kcal/kg	3,813	4,229	3,873	4,228	4,032	3,962	3,888
DM, %	87.75	87.50	81.44	86.42	86.38	85.28	88.48
CP, %	6.82	10.18	7.64	17.11	16.46	14.59	15.26
Ash, %	3.09	4.98	8.77	5.63	2.00	4.23	4.42
NDF, %	9.30	22.57	8.34	24.61	7.99	21.30	30.77
ADF, %	2.03	5.51	3.24	6.77	5.18	5.34	6.75
AEE,[2] %	2.68	10.13	6.83	6.75	2.40	3.62	2.40

[1]Provided the following quantities of vitamins and microminerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,128 IU; vitamin D_3 as cholecalciferol, 2,204 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.58 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 as nicotinamide and nicotinic acid, 44 mg; folic acid, 1.58 mg; biotin, 0.44 mg; Cu, 10 mg as copper sulfate; Fe, 125 mg as iron sulfate; I, 1.26 mg as potassium iodate; Mn, 60 mg as manganese sulfate; Se, 0.3 mg as sodium selenite; and Zn, 100 mg as zinc oxide.

[2]AEE = acid hydrolyzed ether extract.

2009). Diets were analyzed for GE, DM, CP, ash, AEE, ADF, and NDF as described for Exp. 1. Fecal samples and urine were also analyzed for GE (Kim et al., 2009).

Calculations and Statistical Analysis. The ATTD of GE was calculated as previously described (Stein et al., 2004). The amount of energy lost in the feces and urine was calculated and the quantities of DE and ME in each of the 7 diets were calculated as well (Stein et al., 2004). For corn, hominy feed, and bakery meal, DE and ME values were calculated for each ingredient by dividing the DE or ME of the diet by the inclusion rate of the ingredient. The contribution of DE and ME from corn to the diets containing corn gluten meal, corn gluten feed, corn germ meal, or DDGS was subtracted from the DE and ME of these diets, and the DE and ME in each of these ingredients were then calculated by difference (Adeola, 2001). Data were analyzed as described for Exp.1.

RESULTS

Phosphorus Digestibility (Experiment 1)

Daily feed intake (DM basis) was not affected by feed ingredient or microbial phytase (Table 4). Phytase did not influence the daily P intake of pigs fed the diets containing bakery meal, DDGS, corn gluten meal, or corn gluten feed, but daily P intake was greater ($P < 0.05$) for pigs fed the hominy feed and corn germ meal diets and less ($P < 0.05$) for pigs fed the corn diet with phytase than pigs fed the same diets without addition of phytase (ingredient × phytase, $P < 0.05$). There were no differences in fecal P concentration or total daily P excretion between pigs fed the DDGS and corn gluten feed diets without or with phytase, but for all other ingredients, the P concentration in feces and total daily P excretion were less ($P < 0.05$) for pigs fed diets containing phytase than from pigs fed the diets without phytase (ingredient × phytase, $P < 0.05$). Pigs fed the corn and corn gluten meal diets either without phytase or with phytase had the least ($P < 0.05$) daily absorption of P compared with the other diets.

The ATTD of P in ingredients without phytase was greater ($P < 0.05$) in DDGS and corn gluten meal than in corn, hominy feed, bakery meal, and corn germ meal but less ($P < 0.05$) than in corn gluten feed. The ATTD of P in bakery meal and corn germ meal was also greater ($P < 0.05$) than in corn and hominy feed if no phytase was included in the diet. The addition of phytase increased ($P < 0.05$) the ATTD of P in corn, hominy feed, bakery meal, and corn germ meal, but ATTD of P was not improved by addition of phytase to DDGS, corn gluten meal, and corn gluten feed (ingredient × phytase, $P < 0.05$). The ATTD of P in DDGS, corn gluten meal, and corn gluten feed was greater ($P < 0.05$) than in the other ingredients if phytase was added to the diets. The ATTD of P in bakery meal with phytase was greater ($P < 0.05$) than in corn and hominy feed, and the ATTD of P in

Table 4. Effect of feed ingredient and microbial phytase on apparent total tract digestibility (ATTD) and standardized total tract digestibility (STTD) of P in growing pigs, Exp. 1[1,2]

Item	Feed intake, g DM/d	P intake, g/d	P in feces, %	P output, g/d	Absorbed P, g/d	ATTD of P, %	Basal EPL,[3] mg/d	STTD of P,[4] %
Without phytase								
Corn	481	1.6^{g}	2.0^{b}	1.0^{de}	0.6^{h}	36.4^{g}	96.2	42.5^{i}
Hominy feed	467	3.6^{b}	2.1^{b}	2.4^{a}	1.4^{ef}	34.7^{g}	93.4	37.3^{i}
Bakery meal	473	2.6^{cd}	1.9^{b}	1.2^{cd}	1.4^{f}	54.9^{ef}	94.7	58.6^{gh}
DDGS[5]	463	2.2^{f}	0.9^{de}	0.6^{f}	1.6^{def}	72.2^{bc}	92.6	76.5^{bcd}
Corn gluten meal	475	1.0^{h}	2.4^{a}	0.4^{fg}	0.6^{h}	70.6^{bc}	95.0	75.2^{cd}
Corn gluten feed	482	2.4^{cde}	0.7^{ef}	0.5^{fg}	2.0^{abc}	80.7^{a}	96.3	84.6^{ab}
Corn germ meal	489	2.3^{ef}	1.9^{b}	1.2^{c}	1.1^{g}	49.0^{f}	97.8	53.2^{h}
With phytase								
Corn	456	1.1^{h}	1.1^{d}	0.5^{fg}	0.6^{h}	56.1^{ef}	91.2	64.1^{efg}
Hominy feed	494	3.8^{a}	1.5^{c}	1.6^{b}	2.2^{a}	57.6^{de}	98.8	60.1^{fgh}
Bakery meal	472	2.6^{cd}	1.5^{c}	0.8^{e}	1.8^{bcd}	67.5^{c}	94.4	71.2^{de}
DDGS	471	2.2^{f}	0.7^{ef}	0.5^{fg}	1.7^{cde}	78.5^{ab}	94.3	82.8^{abc}
Corn gluten meal	482	1.0^{h}	1.4^{c}	0.2^{h}	0.8^{h}	77.6^{ab}	96.5	87.4^{a}
Corn gluten feed	469	2.4^{def}	0.7^{f}	0.4^{g}	2.0^{ab}	83.1^{a}	93.7	87.1^{a}
Corn germ meal	509	2.6^{c}	1.4^{c}	0.9^{e}	1.7^{cdef}	64.4^{cd}	101.9	68.3^{def}
SEM	17	0.1	0.1	0.1	0.1	3.1	3.4	3.3
P-value								
Ingredient	0.57	<0.01	<0.01	<0.01	<0.01	<0.01	0.57	<0.01
Phytase	0.71	0.79	<0.01	<0.01	<0.01	<0.01	0.71	<0.01
Ingredient × phytase	0.75	<0.01	<0.01	<0.01	<0.01	<0.01	0.75	0.01

[a–i]Values within a column lacking a common superscript letter are different ($P < 0.05$).

[1]Phytase: 2000 phytase units (Optiphos 2000; Enzyvia, Sheridan, IN)/kg.

[2]Data are means of 6 observations per treatment.

[3]EPL = basal endogenous P loss. The daily basal EPL was calculated by multiplying daily DMI by 200 mg/kg DMI (Stein, 2011).

[4]Values for STTD were calculated by correcting values for ATTD for basal EPL.

[5]DDGS = distillers dried grains with solubles.

corn germ meal was also greater ($P < 0.05$) than corn if phytase was added to the diets.

There were no differences in the daily basal endogenous P loss of pigs among experimental diets, and daily basal endogenous P loss was not affected by phytase. The STTD of P in DDGS was greater ($P < 0.05$) than in corn, hominy feed, bakery meal, and corn germ meal, but not different from corn gluten meal and corn gluten feed if no phytase was added to the diets. The STTD of P in bakery meal and corn germ meal was also greater ($P < 0.05$) than in corn and hominy feed, and the STTD of P was greater ($P < 0.05$) in corn gluten feed than in corn gluten meal if no phytase was used. If phytase was added to the diet, the STTD of P in corn, hominy feed, bakery meal, corn gluten meal, and corn germ meal was increased ($P < 0.05$), but that was not the case for DDGS and corn gluten feed (ingredient × phytase, $P < 0.05$). The STTD of P in DDGS, corn gluten meal, and corn gluten feed was greater ($P < 0.05$) than in the other ingredients, and the STTD of P in bakery meal was greater ($P < 0.05$) than in corn and hominy feed if phytase was added to the diets.

Energy Digestibility (Experiment 2)

Gross energy intake was greater ($P < 0.05$) for pigs fed the hominy feed or DDGS diets than pigs fed the other diets, but there were no differences in GE intake among pigs fed diets containing corn, bakery meal, corn gluten meal, corn gluten feed, or corn germ meal (Table 5). Pigs fed the corn, bakery meal, or corn gluten meal diets had less ($P < 0.05$) fecal excretion of GE than pigs fed the hominy feed, DDGS, corn gluten feed, or corn germ meal diets, and pigs fed the corn germ meal diet excreted less ($P < 0.05$) GE in the feces than pigs fed the hominy feed or DDGS diets, but pigs fed the hominy feed diet excreted more ($P < 0.05$) GE in the feces than pigs fed all other diets. The urine excretion of GE was greater ($P < 0.05$) for pigs fed the bakery meal diet than pigs fed all other diets and pigs fed the diet containing corn gluten meal had greater ($P < 0.05$) urine excretion than pigs fed the diets containing corn, hominy feed, or corn germ meal. Pigs fed the corn gluten feed also excreted more ($P < 0.05$) GE in urine than pigs fed the corn and hominy feed diets. The ATTD of GE was greater ($P < 0.05$) for pigs fed the corn, bakery meal, or corn gluten meal diets than pigs fed the other diets, but the ATTD of GE was less ($P < 0.05$) for pigs fed the diet

Table 5. Concentration of digestible and metabolizable energy and apparent total tract digestibility (ATTD) of energy in corn, hominy feed, bakery meal, distillers dried grains with solubles (DDGS), corn gluten meal, corn gluten feed, and corn germ meal, Exp. 2[1]

	Diet								
Item	Corn	Hominy feed	Bakery meal	DDGS	Corn gluten meal	Corn gluten feed	Corn germ meal	SEM	*P*-value
Diets									
GE intake, kcal	4,089^{b}	4,417^{a}	4,068^{b}	4,309^{a}	4,114^{b}	4,140^{b}	4,077^{b}	107	<0.01
GE in feces, kcal	430.8^{d}	940.9^{a}	482.0^{d}	839.6^{b}	411.8^{d}	833.3^{bc}	751.0^{c}	35.6	<0.01
GE in urine, kcal	129.7^{d}	131.6^{d}	270.5^{a}	180.1^{bcd}	212.6^{b}	192.6^{bc}	153.9^{cd}	21.7	<0.01
ATTD of GE, %	89.4^{a}	78.7^{c}	88.2^{a}	80.6^{b}	90.0^{a}	79.9^{bc}	81.6^{b}	0.7	<0.01
DE, kcal/kg	3,410^{b}	3,328^{c}	3,414^{b}	3,407^{b}	3,629^{a}	3,164^{d}	3,172^{d}	28	<0.01
ME, kcal/kg	3,291^{b}	3,202^{c}	3,159^{c}	3,228^{bc}	3,421^{a}	2,981^{d}	3,025^{d}	28	<0.01
Ingredients									
ATTD of GE, %	89.4^{ab}	78.7^{c}	88.2^{b}	72.9^{d}	92.5^{a}	70.6^{d}	73.9^{d}	1.4	<0.01
DE, kcal/kg	3,498^{bc}	3,399^{c}	3,495^{bc}	3,556^{b}	4,896^{a}	3,051^{d}	3,073^{d}	55	<0.01
DE, kcal/kg of DM	4,032^{b}	3,819^{c}	3,951^{bc}	4,062^{b}	5,379^{a}	3,553^{d}	3,437^{d}	61	<0.01
ME, kcal/kg	3,375^{b}	3,271^{b}	3,233^{b}	3,235^{b}	4,006^{a}	2,721^{c}	2,817^{c}	64	<0.01
ME, kcal/kg of DM	3,891^{b}	3,675^{c}	3,655^{c}	3,694^{bc}	4,400^{a}	3,169^{d}	3,150^{d}	72	<0.01

$^{a–d}$Means within a row lacking a common superscript letter differ ($P < 0.05$).

[1]Data are means of 8 observations per treatment.

containing hominy feed than pigs fed the diets containing DDGS or corn germ meal. The concentration of DE in corn, bakery meal, and DDGS diets was greater ($P < 0.05$) than in hominy feed, corn gluten feed, and corn germ meal diets, but less ($P < 0.05$) than in the corn gluten meal diet. The DE in the hominy feed diet was also greater ($P < 0.05$) than in the diets containing corn gluten feed or corn gluten meal. The ME of the corn diet was less ($P < 0.05$) than the ME of the corn gluten meal diet, but greater ($P < 0.05$) than of hominy feed, bakery meal, corn gluten feed, or corn germ meal diets. The ME of the diets containing hominy feed, bakery meal, or DDGS was also greater ($P < 0.05$) than of the ME in the diets containing corn gluten feed or corn germ meal.

The ATTD of GE was greater ($P < 0.05$) in corn gluten meal than in all other ingredients except corn, and the ATTD of GE in corn and bakery meal was greater ($P < 0.05$) than in hominy feed, DDGS, corn gluten feed, and corn germ meal. The ATTD of GE in hominy feed was also greater ($P < 0.05$) than in DDGS, corn gluten feed, and corn germ meal. The DE (as-fed and DM basis) was greater ($P < 0.05$) in corn gluten meal than in all other ingredients. The DE in DDGS (as-fed basis) was greater ($P < 0.05$) than in hominy feed, corn gluten feed, and corn germ meal, and the DE in corn, hominy feed, and bakery meal was also greater ($P < 0.05$) than in corn gluten feed and corn germ meal. The DE in corn and DDGS (DM basis) was greater ($P < 0.05$) than in hominy feed, corn gluten feed, and corn germ meal, and the DE in hominy feed and bakery meal was also greater ($P < 0.05$) than in corn gluten feed and corn germ meal. The ME (as-fed and DM basis) was greater ($P < 0.05$) in corn gluten meal than in all other ingredients. The ME (as-fed basis) in corn, hominy feed, bakery meal, and DDGS was greater ($P < 0.05$) than in corn gluten feed and corn germ meal. The ME (DM basis) was greater ($P < 0.05$) in corn than in hominy feed, bakery meal, corn gluten feed, and corn germ meal but not different from the ME in DDGS. The ME in hominy feed, bakery meal, and DDGS was also greater ($P < 0.05$) than in corn gluten feed and corn germ meal.

DISCUSSION

Corn can be used in the animal feed industry, in the dry milling industry, the corn wet milling industry, or in the dry grind corn processing industry. Products produced from corn include high energy feed, flaking grits, starch, corn oil, and ethanol (Gulati et al., 1996; Serna-Saldivar, 2010). As the main products are produced, corn coproducts are also produced. These coproducts include hominy feed from the dry milling industry, DDGS from the dry grind industry, corn gluten meal and corn gluten feed from the corn wet milling industry, and corn germ meal from either corn wet milling or corn dry grind industries (NRC, 2012). Bakery meal is an ingredient made up of unsold and unsalable products from bakeries and food processing plants (Champe and Church, 1980; Arosemena et al., 1995) and is widely used in the feed industry.

Phosphorus Digestibility (Experiment 1)

The concentration of P in corn, DDGS, and corn gluten feed concur with the values reported by NRC (2012). Phosphorus concentration in hominy feed, bakery meal, and corn gluten meal is slightly greater than the values

reported by Arosemena et al. (1995) and NRC (2012), but they are in agreement with values reported by Sauvant et al. (2004).

The phytate that is present in feed ingredients of plant origin such as corn and SBM binds P and the P, therefore, becomes less digestible (Eeckhout and De Paepe, 1994; Selle and Ravindran, 2008). The phytate concentration in corn that was determined in this experiment is in agreement with the value reported by Almeida and Stein (2012) and NRC (2012), but the phytate concentration in DDGS is slightly less than the value reported by Almeida and Stein (2012) and much less than the value reported by NRC (2012). This variation may be due to variability among ethanol plants in processing, but it is also possible that microbial phytase was included in the enzyme mixture used in the ethanol plant that produced the DDGS because it is estimated that approximately 25% of all ethanol plants in the United States use an enzyme mixture that contains phytase. The phytate concentration in hominy feed determined in this experiment is greater than the value reported by NRC (2012), which may be due to differences among processing facilities in the production of corn grits. We are not aware of other publications where values for the concentration of phytate have been reported for bakery meal and corn germ meal. However, the low phytate concentration in corn gluten feed that was observed in the present experiment indicates that most of the phytate was degraded during processing of this ingredient. Published values for the concentration of phytate in corn gluten feed are much greater (Eeckhout and De Paepe, 1994; NRC, 2012) than the value determined in this experiment, but it is possible that this difference is caused by different product streams being included in corn gluten feed.

The STTD of P in corn and in DDGS concurs with previous values (Pedersen et al., 2007; Almeida and Stein, 2010, 2012). The fact that the responses to microbial phytase was much greater in corn than in DDGS is also in agreement with previous data (Almeida and Stein, 2010, 2012) and is likely a result of the greater concentration of phytate in corn than in DDGS. The STTD of P in corn germ meal that was calculated in this experiment is greater than the value for corn germ reported by Widmer et al. (2007), which is likely a result of the fact that the corn germ meal used in this experiment was from the wet milling industry whereas the corn germ used by Widmer et al. (2007) originated from the dry grind industry.

The observation that the STTD of P was relatively low in corn and hominy feed, intermediate in corn germ meal, and high in DDGS, corn gluten meal, and corn gluten feed is likely a result of the differences in the processing these ingredients have undergone. Corn and hominy feed were not fermented or steeped, and phytate was, therefore, not degraded, which resulted in the low digestibility of P in these ingredients. In contrast, DDGS is fermented and corn gluten meal goes through steeping during production. Corn gluten feed consists of several streams from the wet milling process, including streams that have been steeped or fermented, and corn extractives are also added to corn gluten feed. Fermentation and steeping hydrolyze much of the phytate, which results in a low proportion of P being bound in phytate and a high digestibility of P (Carlson and Poulsen, 2003; Lyberg et al., 2006; Rojas and Stein, 2012). It is, therefore, likely that these differences in processing are the reasons for the greater values for STTD in DDGS, corn gluten meal, and corn gluten feed compared with corn and hominy feed. The observation that microbial phytase had a much greater effect on improving the STTD of P in corn and hominy feed than in DDGS and that no effect was observed for corn gluten feed may be a result of the greater proportion of P being bound to phytate in these ingredients. Therefore, the effect of phytase changes according to the amount of phytate present in the feed ingredient. It appears that there is no or very limited effect of addition of phytase to ingredients, in which less than 25% of P is bound to phytate. The observation that the STTD of P in corn germ meal was intermediate between the STTD in corn and the fermented or steeped coproducts indicates that the time of steeping used in the production of corn germ meal is less than that used for corn gluten feed. Results of the phytate analysis supports this hypothesis and as expected, the effect of microbial phytase on improving the STTD of P in corn germ meal was less than in corn and hominy feed, but greater than in DDGS, corn gluten meal, and corn gluten feed.

The proportion of P that was bound to phytate in bakery meal was less than in corn, which is likely a result of the fact that wheat is mainly used in the production of the food products used to produce bakery meal. Wheat contains more nonphytate-bound P than corn (Eeckhout and De Paepe, 1994). Bakery meal is produced from human consumption products that have gone through different types of processing such as fermentation, steaming, cooking, or baking (Serna-Saldivar, 2010). The mixture of products in bakery meal may change over time, which may result in some variability among sources of bakery meal (Arosemena et al., 1995). The digestibility of Lys in bakery meal is relatively low, indicating that this ingredient is processed at high temperatures (Almeida et al., 2011) and it is also possible that the heat used during processing of bakery meal reduced the concentration of phytate because heat can partly hydrolyze phytate (Martinez-Amezcua and Parsons, 2007).

Energy Digestibility (Experiment 2)

The ATTD of GE and the concentration of DE and ME in corn and DDGS concur with values published by Pedersen et al. (2007), Stein et al. (2006, 2009), and NRC (2012). The greater concentration of GE and the reduced ATTD of GE in DDGS compared with corn observed in this experiment was also reported by Pedersen et al. (2007) and Anderson et al. (2012). This observation is likely due to the high concentration of insoluble fiber in DDGS, which reduces the digestibility of GE and, therefore, decreases the ME concentration compared with the ME in corn (Urriola et al., 2010). It has also been reported that the digestibility of lipids in DDGS is relatively low, which also contributes to a low digestibility of GE (Kim et al., 2013).

The concentration of DE and ME in hominy feed is in close agreement with values reported by NRC (2012) but less than values reported by Stanley and Ewan (1982). It is likely that the reason for the slightly reduced concentration of DE and ME in hominy feed compared with corn is that hominy feed contains more NDF and less starch than corn and the ATTD of GE in hominy feed is, therefore, less than corn. A similar observation was reported by Stanley and Ewan (1982).

The DE and ME in corn gluten meal are in agreement with data reported by Anderson et al. (2012), but greater than values reported by NRC (2012). The greater concentration of DE and ME in corn gluten meal than in corn is also in agreement with data reported by Young et al. (1977) and is mainly a result of the greater concentration of CP and the reduced concentration of fiber in corn gluten meal compared with corn (Stock et al., 2000). Values for the DE and ME in corn gluten meal determined in this experiment are also in close agreement with recently published values for DE and ME in corn gluten meal produced in China (Ji et al., 2012) although lower values for DE in Chinese corn gluten meal also have been published (Guo et al., 2004).

The observation that the concentration of GE and nutrients as well as the DE and ME in corn gluten feed is similar to that in corn germ meal is in agreement with recently published data (Anderson et al., 2012; NRC, 2012) although the DE and ME in corn gluten feed in this experiment is slightly greater than the values published by Anderson et al. (2012). The reduced DE and ME in corn gluten feed compared with corn concur with previous data (Yen et al., 1974; Young et al., 1977), but ME values determined in this experiment are greater than values reported by Yen et al. (1974). In contrast, if corn gluten feed is fed to gestating sows, a greater ME value is observed (Honeyman and Zimmerman, 1991). However, as pointed out, corn gluten feed consists of several different product streams from the wet milling industry and these streams may change over time and vary among sources of corn gluten feed.

Corn germ meal is produced when the oil is extracted from corn germ (Weber et al., 2010), and as a consequence, the concentration of CP and NDF is greater, but the concentration of fat is less, in corn germ meal than in corn germ (Widmer et al., 2007). The reduced concentration of fat in corn germ meal compared with corn germ is likely the reason for the reduced DE and ME in corn germ meal that were determined in this experiment compared with the values reported for corn germ by Widmer et al. (2007), but the ME in corn germ meal obtained in this experiment is in good agreement with the value reported by NRC (2012).

The ME in hominy feed, DDGS, corn gluten feed, and corn germ meal was approximately 74, 68, 63, and 67%, respectively, of the GE in these ingredients whereas the ME of corn was 86% of the GE. The reason for this difference is likely that hominy feed, DDGS, corn gluten feed, and corn germ meal contain much more fiber than corn, which contributes to a low digestibility of energy (Anderson et al., 2012). This observation indicates that there is an opportunity to obtain more energy from hominy feed, DDGS, corn gluten feed, and corn germ meal if the fermentability of the fiber can be increased via chemical, physical, or enzymatic treatments. Research in this area is, therefore, needed.

Conclusions

Distillers dried grains with solubles, corn gluten meal, and corn gluten feed have a greater ATTD and STTD of P than corn, hominy feed, bakery meal, and corn germ meal, but phytase may be included in the diets containing corn, hominy feed, bakery meal, and corn germ meal to improve P digestibility. However, there is no effect of phytase when phytase is included in diets that contain DDGS, corn gluten meal, or corn gluten feed. Corn gluten meal contains more ME than bakery meal and corn coproducts, but ME is greater in corn than in hominy feed, bakery meal, corn gluten feed, and corn germ meal, but not different from the ME in DDGS.

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