Performance and phosphorus balance of pigs fed diets formulated on the basis of values for standardized total tract digestibility of phosphorus

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ABSTRACT: Three experiments were conducted to test the hypotheses that pigs fed diets that are equal in digestible P will perform equally regardless of the concentration of total P in the diets, and that the addition of microbial phytase, distillers dried grains with solubles (DDGS), or a combination of phytase and DDGS will result in a reduction in P excretion. In Exp. 1, a P-free diet and 6 diets containing corn, soybean meal (SBM), or DDGS without or with microbial phytase (500 phytase units per kg) were formulated. Diets were fed for 12 d to 42 pigs (initial BW = 13.5 ± 3.9 kg) housed in metabolism cages that allowed for total collections of feces. Basal endogenous P losses were determined to be 199 mg/kg of DMI for pigs fed the P-free diet. Addition of phytase increased ($P < 0.01$) the standardized total tract digestibility (STTD) of P in corn (64.4 vs. 26.4%) and SBM (74.9 vs. 48.3%), but there was no effect ($P > 0.10$) of the addition of phytase on the STTD of P in DDGS (75.5 vs. 72.9%). In Exp. 2, a total of 160 pigs (initial BW = 11.25 ± 1.95 kg; 4 pigs/pen) were allotted to 4 corn- and SBM-based diets with 2 amounts of phytase (0 or 500 phytase units per kg) and 2 amounts of DDGS (0 or 20%) in a 2 × 2 factorial arrangement of treatments. All diets were formulated to contain 0.32% STTD of P according to the STTD values determined in Exp. 1. Diets were fed for 21 d and results indicated that inclusion of phytase in the diet containing no DDGS tended ($P < 0.10$) to decrease G:F, but inclusion of 20% DDGS in the diets tended ($P < 0.10$) to increase ADG, ADFI, and final BW. In Exp. 3, the diets used in Exp. 2 were fed to 24 pigs (initial BW = 14.6 ± 1.4 kg) that were placed in metabolism cages individually. Feces and urine were collected for 5 d. Phytase and DDGS increased ($P < 0.01$) the apparent total tract digestibility of P in the diets. Absorption of P was greater ($P < 0.05$) in pigs fed corn-SBM-DDGS diets than pigs fed corn-SBM diets, and phytase, DDGS, or the combination of phytase and DDGS reduced ($P < 0.01$) P excretion. In conclusion, the addition of phytase increased the STTD of P in corn and SBM, but had no effect on the STTD of P in DDGS. Diets may be formulated based on STTD values without compromising pig performance, and dietary phytase, DDGS, or the combination of phytase and DDGS will reduce P excretion by growing pigs.

Key words: digestibility, endogenous loss, excretion, phosphorus, phytase, pig

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INTRODUCTION

Phosphorus excretion from pigs can be reduced if phytase is added to diets based on soybean meal (**SBM**) and corn (Cromwell et al., 1995). It is also believed that P excretion can be reduced if distillers dried grains with solubles (**DDGS**) is used because the digestibility of P is greater in DDGS than in corn and SBM (Stein and Shurson, 2009). Values for the apparent total tract digestibility (**ATTD**) of P in corn, SBM, and DDGS have been reported (Bohlke et al., 2005; Pedersen et al., 2007), but values for ATTD do not account for the endogenous P losses (**EPL**). Endogenous P losses can be measured using the regression procedure (Fan et al., 2001), which is believed to yield total EPL, or by using a P-free diet (Petersen and Stein, 2006), which yields basal EPL. If values for ATTD of P are corrected for total EPL, values for true total tract digestibility of P are calculated, whereas values for standardized total tract digestibility (**STTD**) are calculated by correcting ATTD values for basal EPL. For AA, it has been demonstrated that digestibility values based on standardized ileal digestibility of AA and CP are additive in mixed diets, which is not always the case for values based on apparent ileal digestibility (Stein et al., 2005).

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Table 1. Ingredient composition of experimental diets (as-fed basis), Exp. 1

	Corn		SBM[1]		DDGS[1]		
Ingredient, %	0 FTU[2]/kg	500 FTU/kg	0 FTU/kg	500 FTU/kg	0 FTU/kg	500 FTU/kg	P free
Ground corn	97.10	97.10	—	—	—	—	—
Soybean meal (48% CP)	—	—	40.00	40.00	—	—	—
DDGS	—	—	—	—	50.00	50.00	—
Sucrose	—	—	10.00	10.00	20.00	20.00	20.00
Soybean oil	1.00	1.00	3.00	3.00	—	—	4.00
Ground limestone	1.18	1.18	1.20	1.20	1.20	1.20	0.80
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin-mineral premix[3]	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Phytase premix[2]	—	0.03	—	0.03	—	0.03	—
Cornstarch	0.03	—	45.10	45.08	28.10	28.08	49.22
Potassium carbonate	—	—	—	—	—	—	0.40
Magnesium oxide	—	—	—	—	—	—	0.10
Solka-Floc[4]	—	—	—	—	—	—	4.00
Gelatin[5]	—	—	—	—	—	—	20.00
AA mixture[6]	—	—	—	—	—	—	0.78

[1]SBM = soybean meal; DDGS = distillers dried grains with solubles.
[2]FTU = phytase units. Optiphos 2000 (2,000 FTU/g; Enzyvia, Sheridan, IN).
[3]The vitamin-micromineral premix provided the following quantities of vitamins and microminerals per kilogram of complete diet: vitamin A, 11,128 IU; vitamin D_3, 2,204 IU; vitamin E, 66 IU; vitamin K, 1.42 mg; thiamine, 0.24 mg; riboflavin, 6.58 mg; pyridoxine, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid, 23.5 mg; niacin, 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.
[4]Fiber Sales and Development Corp. (Urbana, OH).
[5]Pork gelatin obtained from Gelita Gelatine USA Inc. (Sioux City, IA).
[6]Provided the following quantities (%) of AA to the complete diet: DL-methionine, 0.27; L-threonine, 0.08; L-tryptophan, 0.14; L-histidine, 0.08; L-isoleucine, 0.16; and L-valine, 0.05.

It is, therefore, believed that values for STTD of P are also additive in mixed diets, but this concept has not been experimentally verified. The STTD of P in corn, SBM, and DDGS has not been reported, and the effect of microbial phytase on STTD in those ingredients has not been measured. The objectives of the current experiments were, therefore, to test the following hypotheses: 1) the STTD of P in corn, SBM, and DDGS fed to growing pigs will increase if microbial phytase is used; 2) pigs fed diets that contain equal quantities of STTD of P will perform equally well regardless of the concentration of total P in the diets, and 3) the addition of microbial phytase, DDGS, or a combination of phytase and DDGS to diets fed to pigs will result in a reduction in P excretion.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocols for all 3 experiments.

The pigs used in Exp. 1 were the offspring of Line 337 boars that were mated to C-22 females, whereas the pigs used in Exp. 2 and 3 were the offspring of Landrace boars mated to Yorkshire-Duroc females (Pig Improvement Company, Hendersonville, TN).

Exp. 1 (P Digestibility)

Diets, Animals, and Experimental Design. Seven diets were formulated (Tables 1 and 2). Two diets were based on corn, 2 diets were based on SBM, and 2 diets were based on DDGS. Corn, SBM, or DDGS was the only source of P in the diets, and 1 of the diets from each ingredient contained no phytase, whereas the other diet contained 500 phytase units of microbial phytase per kilogram (Optiphos 2000, Enzyvia, Sheridan, IN). A P-free diet was also formulated. A total of 42 growing barrows (initial BW = 13.5 ± 3.9 kg) were used. Pigs were placed in metabolism cages equipped with a feeder and a nipple drinker and randomly allotted to the 7 dietary treatments with 6 pigs per treatment.

Feeding and Sample Collection. The quantity of feed provided per pig daily was calculated as 3 times the estimated requirement for maintenance energy (i.e., 106 kcal of ME/$kg^{0.75}$; NRC, 1998) and divided into 2 equal meals. Water was available at all times. The initial 5 d was considered an adaptation period to the diet. An indigestible marker was added to the morning meals, which were fed on d 6 and 11, and fecal materials originating from the feed provided from d 6 to 11 were collected according to the marker-to-marker approach (Adeola, 2001). Chromic oxide was used to mark the beginning of collection, whereas ferric oxide was used to mark the end of collection. Fecal samples were stored at −20°C immediately after collection.

Sample Analysis and Data Processing. Fecal samples were dried at 65°C in a forced-air oven and finely ground before analysis. Fecal, diet, and ingredient samples were analyzed in duplicate for DM by oven drying at 135°C for 2 h (method 930.15; AOAC, 2005)

Table 2. Analyzed nutrient composition of diets (as-fed basis), Exp. 1

	Corn		SBM[1]		DDGS[1]		
Nutrient	0 FTU[2]/kg	500 FTU/kg	0 FTU/kg	500 FTU/kg	0 FTU/kg	500 FTU/kg	P free
DM, %	90.95	90.91	94.20	93.97	94.16	94.12	95.66
CP, %	8.65	8.50	20.54	18.01	14.61	13.63	21.40
ADF, %	2.44	2.32	2.23	2.30	4.90	5.05	3.34
NDF, %	10.16	10.02	6.42	6.14	18.95	23.89	5.75
P, %	0.28	0.28	0.28	0.29	0.43	0.41	0.01
Ca,[3] %	0.45	0.45	0.57	0.57	0.53	0.53	0.28
Phytase,[2] FTU/kg	<70	630	<70	680	180	820	—
Indispensable AA, %							
Arg	0.38	0.41	1.35	1.37	0.65	0.64	1.45
His	0.21	0.22	0.50	0.50	0.37	0.36	0.24
Ile	0.26	0.28	0.91	0.89	0.52	0.50	0.40
Leu	0.85	0.91	1.45	1.46	1.53	1.45	0.56
Lys	0.26	0.28	1.23	1.24	0.50	0.49	0.71
Met	0.15	0.15	0.25	0.25	0.27	0.26	0.38
Phe	0.36	0.38	0.95	0.95	0.64	0.62	0.39
Thr	0.25	0.27	0.70	0.73	0.48	0.45	0.39
Trp	0.06	0.06	0.35	0.38	0.16	0.16	0.15
Val	0.35	0.37	0.94	0.91	0.69	0.66	0.50
Dispensable AA, %							
Ala	0.53	0.57	0.84	0.84	0.97	0.94	1.61
Asp	0.49	0.53	2.15	2.17	0.89	0.86	1.07
Cys	0.16	0.16	0.27	0.27	0.26	0.25	0.02
Glu	1.29	1.38	3.53	3.59	2.23	2.22	1.88
Gly	0.30	0.32	0.84	0.84	0.57	0.57	4.31
Pro	0.58	0.63	0.88	0.89	0.95	0.90	2.33
Ser	0.31	0.34	0.86	0.92	0.55	0.52	0.55
Tyr	0.24	0.26	0.68	0.69	0.49	0.47	0.13

[1]SBM = soybean meal; DDGS = distillers dried grains with solubles.
[2]FTU = phytase units. Optiphos 2000 (2,000 FTU/g; Enzyvia, Sheridan, IN).
[3]Values for Ca were calculated (NRC, 1998) rather than analyzed.

and for P by inductively coupled plasma spectroscopy (method 985.01; AOAC, 2005) after wet ash sample preparation (method 975.03; AOAC, 2005). Diets and ingredients were analyzed for AA [method 982.30 E (a, b, c); AOAC, 2005], ADF (method 973.18; AOAC, 2005), and NDF (Holst, 1973). Diets were also analyzed for CP by combustion (method 990.03; AOAC, 2005). Corn, SBM, DDGS, and all diets were analyzed for phytase activity (Phytex Method, version 1, Eurofins, Des Moines, IA).

The ATTD (%) of P in each diet was calculated according to the following equation:

$$\text{ATTD (\%)} = [(\text{Pi} - \text{Pf})/\text{Pi}] \times 100,$$

where Pi is the total P intake (g) from d 6 to 11 and Pf is the total fecal P output (g) originating from the feed that was provided from d 6 to 11.

The basal EPL (mg/kg of DMI) were measured from pigs fed the P-free diet according to the following equation:

$$\text{EPL (mg/kg of DMI)} = ([\text{Pf}/\text{Fi}] \times 1{,}000 \times 1{,}000),$$

where Fi is the total feed (g of DM) intake from d 6 to 11. The daily EPL loss in pigs fed the P-containing diets was calculated by multiplying the calculated EPL per kilogram of DMI by the DMI of each pig.

The STTD of P was calculated using the following equation:

$$\text{STTD (\%)} = [\text{Pi} - (\text{Pf} - \text{EPL})/\text{Pi}] \times 100.$$

Data were analyzed using the GLM procedure (SAS Inst. Inc., Cary, NC). The UNIVARIATE procedure in SAS was used to confirm that variances were homogeneous and also to analyze for outliers, but no outliers were identified. The ATTD and STTD of P in corn, SBM, and DDGS without and with microbial phytase were compared within each ingredient. The LSMEANS statement was used to calculate mean values. Pig was the experimental unit and an α-value of 0.05 was used to assess significance among means.

Exp. 2 (Performance)

Diets, Animals, and Experimental Design. A total of 160 pigs (initial BW = 11.3 ± 2.0 kg) were weaned at approximately 20 d of age, assigned to pens with 4 pigs per pen, and fed a common phase 1 diet. On d 11 postweaning, pens were randomly allotted to 4 di-

Table 3. Ingredient composition of experimental diets (as-fed basis), Exp. 2 and 3

	Corn-SBM[1]		Corn-SBM-DDGS[1]	
Ingredient, %	0 FTU[2]/kg	500 FTU/kg	0 FTU/kg	500 FTU/kg
Corn	61.76	62.08	47.89	48.15
SBM (48% CP)	32.00	32.00	26.00	26.00
DDGS	—	—	20.00	20.00
Soybean oil	3.00	3.00	3.00	3.00
Limestone	0.85	1.31	1.15	1.52
Dicalcium phosphate	1.15	0.35	0.65	—
L-Lys·HCl	0.28	0.28	0.40	0.40
DL-Met	0.13	0.13	0.08	0.08
L-Thr	0.13	0.13	0.11	0.11
L-Trp	—	—	0.02	0.02
Salt	0.40	0.40	0.40	0.40
Vitamin-mineral premix[3]	0.30	0.30	0.30	0.30
Phytase[2]	—	0.03	—	0.03

[1]SBM = soybean meal; DDGS = distillers dried grains with solubles.

[2]FTU = phytase units. Optiphos 2000 (2,000 FTU/g, Enzyvia, Sheridan, IN).

[3]The vitamin-micromineral premix provided the following quantities of vitamins and microminerals per kilogram of complete diet: vitamin A, 11,128 IU; vitamin D_3, 2,204 IU; vitamin E, 66 IU; vitamin K, 1.42 mg; thiamine, 0.24 mg; riboflavin, 6.58 mg; pyridoxine, 0.24 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid, 23.5 mg; niacin, 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.

ets with 2 amounts of DDGS (0 or 20%) and 2 amounts of phytase (0 or 500 phytase units/kg, Optiphos 2000, Enzyvia) in a 2 × 2 factorial arrangement of treatments with 10 replicate pens per treatment. These diets (Tables 3 and 4) were fed for 3 wk. All diets were formulated to contain 0.32% STTD of P, and values for the concentration of STTD of P in corn, SBM, and DDGS without and with phytase that were measured in Exp. 1 were used to formulate the diets used in Exp. 2. For dicalcium phosphate, a value of 88% for STTD was used (Petersen and Stein, 2006). Pens were 1.2 × 1.4 m with fully slatted floors, and feed and water were provided on an ad libitum basis throughout the experiment.

Sample Analysis and Data Processing. Individual pig BW was recorded at the beginning and at the conclusion of the experiment. Daily feed allotments were recorded as well. Diets were analyzed for phytase, AA, ADF, NDF, CP, DM, and P as described for Exp. 1. Diets were also analyzed for Ca by inductively coupled plasma spectroscopy (method 985.01; AOAC, 2005) after wet ash sample preparation (method 975.03; AOAC, 2005). At the conclusion of the experiment, data were summarized to calculate ADG, ADFI, and G:F for each pen and treatment group. Data were analyzed as a 2 × 2 factorial using the MIXED procedure of SAS. The UNIVARIATE procedure was used to verify the homogeneity of variances and to analyze for outliers, but no outliers were identified. The model included DDGS, phytase, and the interaction between DDGS and phytase as the fixed effects, whereas block was included as a random effect. The pen was the experimental unit for all calculations and an α-level of 0.05 was used to assess significance among means. A *P*-value between 0.05 and 0.10 was considered a trend.

Exp. 3 (P Balance)

The 4 diets used in Exp. 2 were also used in Exp. 3. Twenty-four pigs (initial BW = 14.6 ± 1.4 kg) were placed in metabolism cages and allotted to the 4 experimental diets with 6 pigs per diet. The quantity of feed provided per pig daily was calculated as 3 times the estimated requirement for maintenance energy and divided into 2 equal meals. At each feeding, unconsumed feed in the feeders was removed and weighed. At the conclusion of the experiment, the unconsumed feed was mixed within pig and analyzed for DM, P, and Ca, and the amount of DM, P, and Ca in the unconsumed feed was subtracted from the quantity of DM, P, and Ca that was provided to the pig. Water was available at all times. The initial 5 d was considered an adaptation period to the diet. During the next 5 d, urine was collected in buckets containing 20 mL of sulfuric acid. Fecal samples were also collected over a 5-d period using the marker-to-marker procedure as described for Exp. 1.

Feces and urine were analyzed for Ca and P as described for Exp. 2. The ATTD of P and Ca was calculated as described for Exp. 1. The retention of P was calculated as previously outlined (Petersen and Stein, 2006) using the following equation:

$$Pr = \{[Pi - (Pf + Pu)]/Pi\} \times 100,$$

where Pr is P retention (%), Pi is the intake of P (g), Pf is the fecal output of P, and Pu is the urinary output of P (g) over the collection period. The retention of Ca was also calculated using this equation. Data were analyzed as described for Exp. 2.

Table 4. Nutrient composition of diets (as-fed basis), Exp. 2 and 3

	Corn-SBM[1]		Corn-SBM-DDGS[1]	
Nutrient	0 FTU[2]/kg	500 FTU/kg	0 FTU/kg	500 FTU/kg
DM, %	85.92	85.02	84.31	85.99
CP, %	19.29	17.93	20.55	20.83
ADF, %	2.69	2.64	4.31	4.57
NDF, %	10.26	10.68	18.40	16.62
Ca, %	0.62	0.66	0.60	0.60
P, %	0.59	0.44	0.58	0.48
ATTD[3] of P, % of diet P	49.8	66.4	51.7	66.3
STTD P,[4] %	0.32	0.32	0.32	0.32
Phytase,[2] FTU/kg	190	690	140	680
Indispensable AA, %				
Arg	1.22	1.26	1.27	1.26
His	0.51	0.53	0.57	0.57
Ile	0.81	0.84	0.88	0.88
Leu	1.53	1.59	1.86	1.85
Lys	1.29	1.37	1.37	1.38
Met	0.38	0.43	0.41	0.40
Phe	0.88	0.92	0.98	0.97
Thr	0.75	0.81	0.81	0.82
Trp	0.24	0.22	0.24	0.24
Val	0.91	0.94	1.03	1.02
Dispensable AA, %				
Ala	0.89	0.93	1.10	1.09
Asp	1.86	1.95	1.90	1.89
Cys	0.30	0.31	0.34	0.34
Glu	3.13	3.27	3.37	3.34
Gly	0.77	0.81	0.85	0.85
Pro	0.96	1.00	1.16	1.16
Ser	0.69	0.76	0.76	0.75
Tyr	0.59	0.61	0.69	0.66

[1]SBM = soybean meal; DDGS = distillers dried grains with solubles.
[2]FTU = phytase units. Optiphos 2000 (2,000 FTU/g, Enzyvia, Sheridan, IN).
[3]Calculated based on values for apparent total tract digestibility (ATTD) in corn, SBM, and DDGS obtained in Exp. 1. For dicalcium phosphate, a value for ATTD of P of 81% was used (Petersen and Stein, 2006).
[4]STTD P = standardized total tract digestible P; values calculated based on digestibility values measured in Exp. 1. For dicalcium phosphate, a value of 88% was used (Petersen and Stein, 2006).

RESULTS

Exp. 1 (P Digestibility)

Pigs remained healthy and readily consumed their diets throughout the experiment. Feed intake, P intake, and fecal output were not affected by the absence or presence of phytase in corn, SBM, or DDGS (Table 5). Phosphorus concentration in feces was reduced from 1.98 to 1.15% ($P < 0.001$) in pigs fed corn and from 2.84 to 1.84% ($P < 0.001$) in pigs fed SBM when phytase was used. The daily P output in feces was also reduced from 0.97 to 0.52 g ($P < 0.05$) for corn and from 0.81 to 0.48 g ($P < 0.001$) for SBM when phytase was added to the diets. In contrast, there was no difference in P concentration in feces or in P output in feces when phytase was added to the DDGS diet. The ATTD of P increased ($P < 0.001$) from 19.9 to 57.8% for corn and from 41.5 to 68.4% for SBM when phytase was added to the diets, but the ATTD of P in DDGS was not affected by the addition of phytase. The basal EPL was measured at 199 mg/kg of DMI in pigs fed the P-free diet. The calculated daily basal EPL in pigs fed the P-containing diets was not influenced by the presence of phytase in the diet regardless of the ingredients used. The STTD of P increased ($P < 0.001$) in corn and SBM when phytase was used (from 26.4 to 64.4% and 48.3 to 74.9%, respectively), but the STTD of P in DDGS without phytase (72.9%) was not different from the STTD of P in DDGS with phytase (75.5%).

Exp. 2 (Performance)

The initial BW of pigs was similar across treatments (Table 6). After 21 d, final BW was recorded and no difference was detected among treatments although pigs fed the corn-SBM-DDGS diets tended ($P < 0.10$) to have a greater final BW than pigs fed the corn-SBM diets. There was also a tendency ($P < 0.10$) for pigs fed corn-SBM-DDGS diets to have a greater ADG and ADFI than pigs fed corn-SBM diets, but there was no effect of phytase on ADG or ADFI. The interaction between phytase and DDGS was significant ($P < 0.05$) for G:F. Inclusion of phytase in the diet containing no DDGS tended ($P < 0.10$) to decrease G:F from 0.661 to

0.614, whereas G:F was not affected by the addition of phytase to the diet containing 20% DDGS.

Exp. 3 (P Balance)

No differences in ADFI were observed among treatments (Table 7), but the daily P intake was less ($P < 0.01$) by pigs fed diets containing phytase than by pigs fed diets containing no phytase. Fecal P output was reduced ($P < 0.01$) by pigs fed diets containing phytase or DDGS compared with pigs fed the diet without phytase or DDGS. However, phytase reduced fecal P output in the corn-SBM diet, but not in the corn-SBM-DDGS diet, resulting in an interaction ($P < 0.01$). The ATTD of P increased ($P < 0.01$) from 56.1 to 71.5% in the corn-SBM diet and from 62.3 to 74.1% in the corn-SBM-DDGS diet when phytase was used. Inclusion of DDGS in the corn-SBM diet also increased ($P < 0.01$) the ATTD of P. Urine P output was reduced ($P < 0.01$) when phytase was added to the diets, but DDGS did not affect urinary P output. Phosphorus absorption was greater ($P < 0.05$) by pigs fed corn-SBM-DDGS diets than by pigs fed corn-SBM diets, but there was no effect of phytase on P absorption. Phytase improved ($P < 0.01$) P retention in the corn-SBM diet from 56.03 to 71.48% and in the corn-SBM-DDGS diet from 62.16 to 74.01%, but when calculated as grams per day, P retention was not affected by the addition of phytase to the diet. However, pigs fed diets containing DDGS retained more P ($P < 0.05$) than pigs fed diets containing no DDGS. Phosphorus excretion was reduced ($P < 0.01$) by phytase and DDGS, but in the diet containing both phytase and DDGS, P excretion was not reduced compared with the corn-SBM diet with phytase (interaction, $P < 0.01$).

There was a tendency ($P = 0.07$) for an increase in Ca intake when phytase was added to the diets. Fecal Ca output was reduced ($P < 0.01$) from 1.21 to 0.85 g/d, and from 1.12 to 0.75 g/d when phytase was added to the corn-SBM and corn-SBM-DDGS diets, respectively. The ATTD of Ca increased ($P < 0.01$) in the corn-SBM diet from 69.65 to 80.42% and in the corn-SBM-DDGS diet from 71.22 to 81.04% when phytase was used. Likewise, Ca absorption increased ($P < 0.01$) in the corn-SBM diet from 2.71 to 3.49 g/d and in the corn-SBM-DDGS diet from 2.80 to 3.20 g/d when phytase was used. The inclusion of DDGS in the diets decreased ($P < 0.01$) urine Ca output, but phytase increased ($P < 0.01$) urine Ca output from 0.24 to 0.74 g/d in corn-SBM diets and 0.14 to 0.42 g/d in corn-SBM-DDGS diets. When Ca retention was calculated as grams per day, no differences among treatments were observed. However, Ca retention measured as a percentage of intake was greater ($P < 0.05$) and Ca excretion was less ($P < 0.05$) by pigs fed diets containing DDGS compared with pigs fed diets without DDGS. There were, however, no effects of phytase on Ca retention or on Ca excretion.

Table 5. Effects of phytase[1] on P balance, apparent total tract digestibility (ATTD), and standardized total tract digestibility (STTD) of P in corn, soybean meal (SBM), and distillers dried grains with solubles (DDGS), Exp. 1[2]

	Corn				SBM				DDGS			
Item	0 FTU[1]/kg	500 FTU/kg	SEM	*P*-value	0 FTU/kg	500 FTU/kg	SEM	*P*-value	0 FTU/kg	500 FTU/kg	SEM	*P*-value
Feed intake, g/d	423	433	35	0.885	505	524	11	0.383	497	495	16	0.943
P intake, g/d	1.19	1.21	0.10	0.887	1.42	1.52	0.03	0.125	2.14	2.03	0.07	0.440
Fecal output, g/d	48.94	44.97	3.80	0.613	28.56	26.01	0.87	0.175	76.74	75.57	2.70	0.833
P in feces, %	1.98	1.15	0.05	0.001	2.84	1.84	0.06	0.001	0.88	0.78	0.04	0.326
P output, g/d	0.97	0.52	0.08	0.013	0.81	0.48	0.02	0.001	0.66	0.59	0.03	0.221
ATTD of P, %	19.90	57.80	2.80	0.001	41.50	68.40	1.78	0.001	68.60	71.00	1.97	0.557
Basal EPL,[3] mg/d	76.67	81.67	0.01	0.682	95.00	98.33	0.00	0.401	95.00	93.33	0.00	0.765
STTD of P,[4] %	26.40	64.40	2.78	0.001	48.30	74.90	1.78	0.001	72.90	75.50	1.97	0.523

[1]Optiphos 2000 (2,000 FTU/g, Enzyvia, Sheridan, IN). FTU = phytase units.
[2]Data are means of 6 observations per treatment.
[3]EPL = endogenous P loss. This value was measured from pigs fed the P-free diet at 199 mg/kg of DMI. The daily basal EPL (mg/d) for each diet was calculated by multiplying the EPL (mg/kg of DMI) by the daily DMI of each diet.
[4]Values for STTD were calculated by correcting values of ATTD for basal endogenous losses.

Table 6. Effects of distillers dried grains with solubles (DDGS)[1] and phytase[2] on growth performance of weanling pigs, Exp. 2[3]

	Corn-SBM[4]		Corn-SBM-DDGS			*P*-value		
Item	0 FTU[2]/kg	500 FTU/kg	0 FTU/kg	500 FTU/kg	SEM	DDGS	Phytase	DDGS × phytase
Initial BW, kg	11.14	11.16	11.14	11.15	0.37	0.234	0.129	0.606
Final BW, kg	21.79	21.30	21.87	21.96	0.54	0.075	0.334	0.155
ADG, kg	0.507	0.483	0.511	0.515	0.011	0.067	0.303	0.147
ADFI, kg	0.772	0.789	0.811	0.806	0.025	0.065	0.665	0.465
G:F	0.661	0.614	0.634	0.640	0.012	0.952	0.052	0.014

[1]Diets contained 20% DDGS.
[2]Optiphos 2000 (Enzyvia, Sheridan, IN). FTU = phytase units.
[3]Data are means of 10 observations per treatment.
[4]SBM = soybean meal.

DISCUSSION

In most diets fed to pigs in the United States, corn and SBM are the main ingredients. Most of the organic P in these feed ingredients is bound in the form of phytate (Erdman, 1979), which is poorly digested by pigs because of the lack of phytase in the gastrointestinal tract of pigs (Pointillart et al., 1984). However, addition of microbial phytase to diets fed to pigs increases P digestibility because phytase partially degrades phytate in the stomach and small intestine, which results in release of P that can be absorbed (Maga, 1982).

Values for the ATTD of P in corn and SBM that were measured in the current experiment are in agreement with values reported by Bohlke et al. (2005) and Pedersen et al. (2007). The ATTD of P in DDGS was reported previously, with values ranging from 50 to 68% (Pedersen et al., 2007; Stein et al., 2009) and the ATTD of P in DDGS measured in this experiment is similar to the greatest values reported. This observation confirms that the ATTD of P in DDGS is much greater than in corn.

The total EPL has been measured using the regression method, which resulted in values between 70 mg/kg of DMI (Dilger and Adeola, 2006; Pettey et al., 2006) and 670 mg/kg of DMI (Shen et al., 2002). In the current experiment, the basal EPL was measured by feeding a P-free diet, and a value of 199 mg/kg of DMI was obtained. This value is within the range (139 to 211 mg/kg of DMI) that has been reported in pigs fed a P-free diet (Petersen and Stein, 2006; Stein et al., 2006; Widmer et al., 2007).

To our knowledge, the STTD of P in corn, SBM, and DDGS has not been reported previously. However, the true total tract digestibility of P in corn is 59% (Shen et al., 2002), and in SBM, the true total tract digestibility of P has been reported to be between 41 and 59% (Fan et al., 2001; Ajakaiye et al., 2003; Akinmusire and Adeola, 2009). Values for the STTD of P in corn and SBM that were calculated in the present experiment (26 and 48%, respectively) are less than the values for true total tract digestibility because STTD values are corrected only for basal EPL, whereas values for true total tract digestibility are corrected for total EPL. Therefore, it is expected that values for STTD are less than values for true total tract digestibility.

Phytase supplementation increased the ATTD and STTD of P in corn and SBM, which was expected because phytate is degraded by phytase (Selle and Ravindran, 2008), and more P is released in the stomach and small intestine when phytase is added to the diet. In the present experiment, the ATTD of P in SBM increased from 41.5 to 68.4% when phytase was used, and these values are in agreement with the ATTD of P in SBM without and with phytase (38.6 and 71.2%, respectively) that were reported recently (Akinmusire and Adeola, 2009). During processing of corn in ethanol plants, a portion of the phytate is hydrolyzed, which is the reason for the greater ATTD of P in DDGS than in corn (Stein and Shurson, 2009). Because of the decreased concentration of phytate in DDGS, phytase is not as effective in increasing the digestibility of P in DDGS as in corn and SBM. To our knowledge, no other data for the ATTD or the STTD of P in DDGS with phytase have been reported.

To compensate for the reduced digestibility of P in corn and SBM, inorganic P in the form of dicalcium phosphate is usually added to diets fed to pigs, but because of the increased digestibility of P in diets containing phytase or DDGS, less inorganic P is needed in the diet if phytase or DDGS is used. We hypothesized that if diets are formulated to contain the same STTD P, no differences in pig performance would be observed, regardless of the quantity of inorganic P in the diet. In Exp. 2, therefore, all diets were formulated to contain 0.32% STTD P and the inclusion of dicalcium phosphate was reduced in the diets containing phytase or DDGS and no inorganic P was used in the diet containing both phytase and DDGS. The tendency for a reduced G:F for pigs fed the corn-SBM diet containing phytase compared with pigs fed the same diet without phytase was surprising. This response has not been observed in previous experiments with phytase, and we did not make a similar observation in the DDGS-containing diet with phytase. The fact that P retention was similar for the diet containing phytase as for the

Table 7. Phosphorus and Ca balance, and apparent total tract digestibility (ATTD) of P for pigs fed corn-soybean meal (SBM) diets or corn-SBM-distillers dried grains with solubles (DDGS) diets without or with microbial phytase,[1] Exp. 3[2]

	Corn-SBM		Corn-SBM-DDGS[3]			*P*-value		
Item	0 FTU[1]/kg	500 FTU/kg	0 FTU/kg	500 FTU/kg	SEM	DDGS	Phytase	DDGS × phytase
Feed intake, g/d	633	658	653	658	23	0.611	0.445	0.618
P intake, g/d	3.74	2.89	3.79	3.16	0.13	0.178	<0.01	0.351
Fecal P output, g/d	1.68	0.82	1.43	0.82	0.04	<0.01	<0.01	<0.01
ATTD of P, %	56.10	71.50	62.30	74.10	1.24	<0.01	<0.01	0.153
Urine P output, mg/d	2.55	1.32	3.44	1.16	0.65	0.559	0.011	0.399
Absorbed P, g/d	2.05	2.07	2.35	2.33	0.13	0.029	0.991	0.829
P retention, g/d	2.05	2.07	2.35	2.33	0.13	0.029	0.991	0.879
P retention, %	56.03	71.48	62.16	74.01	1.23	<0.01	<0.01	0.156
P excretion, g/d	1.68	0.82	1.43	0.82	0.04	<0.01	<0.01	<0.01
Ca intake, g/d	3.93	4.34	3.92	3.95	0.15	0.108	0.078	0.125
Fecal Ca output, g/d	1.21	0.85	1.12	0.75	0.08	0.230	<0.01	0.940
ATTD of Ca, %	69.65	80.42	71.22	81.04	2.22	0.613	<0.01	0.824
Urine Ca output, g/d	0.24	0.74	0.14	0.42	0.05	<0.01	<0.01	0.045
Absorbed Ca, g/d	2.72	3.49	2.80	3.20	0.17	0.493	<0.01	0.232
Ca retention, g/d	2.48	2.75	2.66	2.78	0.15	0.566	0.231	0.701
Ca retention, %	63.24	63.44	67.70	70.49	2.63	0.041	0.577	0.623
Ca excretion, g/d	1.45	1.59	1.26	1.17	0.10	<0.01	0.823	0.277

[1]Optiphos 2000 (Enzyvia, Sheridan, IN). FTU = phytase units.
[2]Data represent the mean of 6 observations per treatment.
[3]Diets contained 20% DDGS.

control diet indicates that the tendency for a reduced G:F for the pigs fed the phytase-containing diet was not caused by a P deficiency. It is, however, possible that the Ca:P ratios in the diets may have influenced the G:F. The analyzed Ca and P concentrations of the diets used in Exp. 2 and 3 indicate that the concentration of Ca was slightly greater and P concentration was less in the corn-SBM diet containing phytase compared with the diet containing no phytase, which resulted in differences in the Ca:P ratios between these 2 diets. A Ca:P ratio at or greater than 1.5:1 may reduce the feed efficiency of growing pigs (Liu et al., 1998; Brady et al., 2002) compared with pigs fed diets with a narrower Ca:P ratio.

Differences in Ca:P ratios may also influence measured values for the ATTD of P in feed ingredients (Liu et al., 1998). The Ca:P ratios in Exp. 1 varied among ingredients, but the ratio was kept constant within each ingredient regardless of whether or not phytase was included in the diet. It is, therefore, unlikely that the Ca:P ratios influenced the response to phytase measured in Exp. 1. The fact that we obtained ATTD values for corn, SBM, and DDGS that agree with previous data also indicates that the ratios used in Exp. 1 did not influence the results. However, the effect of the interaction between phytase and Ca:P ratios on measured values for ATTD and STTD of P in feed ingredients is an area that has not been well studied and something that should be addressed in the future.

The fact that we did not observe a difference in performance among pigs fed the 4 diets in Exp. 2 indicates that values for STTD of P can be used in diet formulation and that no inorganic P is needed in the diet if both phytase and DDGS are used. We are not aware of any other data illustrating the consequences of formulating diets based on the STTD of P, and we believe that this is the first time it is demonstrated that pigs can be fed diets containing no inorganic P from 11 kg if phytase and DDGS are included in the diet.

As expected, the excretion of P from the pigs was reduced if phytase or DDGS was added to the diet because the total concentration of P was less in these diets than the diet containing no phytase or DDGS. However, the retention of P was not reduced when phytase was used, and pigs fed the diets containing DDGS actually had a greater retention of P than pigs fed the diets without DDGS, as demonstrated in Exp. 3. These observations show that the values for the STTD of P that were measured in Exp. 1 did not overestimate the digestibility of P in corn, SBM, or DDGS. The increase in the ATTD of P in the diets used in Exp. 3, as phytase was added to the diets, is also in agreement with the values obtained in Exp. 1. The small, but statistically significant, reductions in urinary P in both groups of pigs fed phytase-containing diets compared with pigs fed diets containing no phytase might indicate that the STTD of P in the phytase-containing ingredients was slightly overestimated. However, these differences are so small that they are likely to have no practical importance. This conclusion is supported by the small, but nonsignificant, differences in P retention between pigs fed diets containing phytase and no phytase, which were 10 to 20 times greater than the small differences in urine P output.

Results of Exp. 3 also indicated that although the ATTD of P in DDGS is not increased when phytase is added (Exp. 1), the ATTD of P in a corn-SBM-DDGS diet is improved by phytase. The reason for this observation is that corn and SBM contain phytate, which can serve as substrate for phytase. Therefore, the improvement in the ATTD of P by microbial phytase in a mixed diet containing corn, SBM, and DDGS is due to the presence of phytate in corn and SBM.

The ATTD of Ca in the diets used in Exp. 3 increased as phytase was added to the diets although most of the Ca in the diets was inorganic Ca from limestone and dicalcium phosphate. These results are in agreement with data reported by Guggenbuhl et al. (2007), which also indicated that phytase increased the ATTD of Ca. One possible mechanism by which Ca absorption is increased with phytase is by phytate hydrolysis reducing phytate esters and therefore reducing the ability of phytate to chelate Ca. As a result, the formation of an insoluble Ca-phytate complex is reduced and Ca availability is increased when phytase is added to the diet (Selle et al., 2009). This may also explain why a smaller Ca:P ratio is recommended in diets containing phytase than diets containing no phytase (Lei et al., 1994; Liu et al., 1998).

The reduction in urinary Ca output for pigs fed the DDGS-containing diets compared with pigs fed the diets without DDGS is most likely a consequence of the increased P retention for pigs fed these diets. Bone tissue synthesis requires both P and Ca and as more P is retained, more Ca is also needed to synthesize bones, which results in less Ca being excreted in the urine (Stein et al., 2006).

The 3 experiments were all relatively short in duration and Ca and P status of pigs may be influenced in the short term by changes in the concentration of Ca and P that are stored in bone tissue of the pigs. The fact that no differences in P retention were observed within each combination of diets, however, indicates that results of the 3 experiments were not influenced by changes in bone Ca and P concentrations; however, longer term experiments need to be conducted to verify this hypothesis.

Conclusions

The results of the present experiments indicate that diets for pigs may be formulated based on STTD of P. If phytase, DDGS, or the combination of phytase and DDGS is used, P excretion is reduced and diets that contain much less inorganic P than conventional diets may be used without reducing pig performance. More research is needed to determine STTD of P in other feed ingredients and also to estimate the STTD of P requirements. If such data are generated, diets can be formulated based on STTD of P, which may result in more accurate formulation and in a reduction in P excretion.

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