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Standardized total tract digestibility of phosphorus in copra meal, palm kernel expellers, palm kernel meal, and soybean meal fed to growing pigs

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ABSTRACT: Sixty-six barrows (initial BW: 27.4 ± 2.8 kg) were used to determine the standardized total tract digestibility (STTD) of P in copra meal (CM), palm kernel expellers from Indonesia (PKE-IN), palm kernel expellers from Costa Rica (PKE-CR), palm kernel meal from Costa Rica (PKM), and soybean meal (SBM) without or with exogenous phytase. Pigs were housed individually in metabolism cages and allotted to 11 diets with 6 replicate pigs per diet in a generalized randomized block design. Five diets were formulated by mixing cornstarch and sugar with CM, PKE-IN, PKE-CR, PKM, or SBM. Five additional diets, which were identical to the initial 5 diets but supplemented with 800 units of phytase, were also formulated. A P-free diet was used to measure basal endogenous losses of P by the pigs. Feces were collected for 5 d using the marker to marker approach after a 5-d adaptation period. Analyzed total P in CM, PKE-IN, PKE-CR, PKM, and SBM was 0.52, 0.51, 0.53, 0.54, and 0.67%, respectively. Phytate P was 0.22, 0.35, 0.38, 0.32, and 0.44% in CM, PKE-IN, PKE-CR, PKM, and SBM, respectively. Addition of phytase increased ($P < 0.05$) the apparent total tract digestibility (ATTD) of P from 60.6 to 80.8, 27.3 to 56.5, 32.6 to 59.9, 48.9 to 64.1, and 41.1 to 72.2% in CM, PKE-IN, PKE-CR, PKM, and SBM, respectively. The ATTD of P in CM was greater ($P < 0.05$) than in any of the other ingredients. The ATTD of P in SBM and PKM was greater ($P < 0.05$) than in PKE-IN, with PKE-CR being intermediate. The STTD of P increased ($P < 0.05$) from 70.6 to 90.3, 37.6 to 66.4, 43.2 to 69.9, 57.9 to 73.5, and 49.6 to 81.1% in CM, PKE-IN, PKE-CR, PKM, and SBM, respectively, when microbial phytase was added to the diets. When expressed as a percentage of total P, phytate P concentration in the ingredient negatively affected ($P < 0.05$) the ATTD of P (107.09 – 1.0564 × % phytate P; $R^2 = 87.1$) and the STTD of P (116.3 – 1.0487 × % phytate P; $R^2 = 89.4$). In conclusion, microbial phytase increased P digestibility of CM, PKM, PKE-CR, PKE-IN, and SBM when fed to growing pigs, and the concentration of phytate P affects the response to microbial phytase.

Key words: copra meal, palm kernel expellers, palm kernel meal, phosphorus, phytase, pigs

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INTRODUCTION

Copra and palm kernel ingredients are coproducts of the coconut and palm oil industries. Copra meal (**CM**) is produced after extracting the oil from the dried coconut kernels using solvent (hexane) extraction. Palm kernel oil may be mechanically expelled or solvent extracted, and the coproducts from these 2 procedures are palm kernel expellers (**PKE**) and palm kernel meal (**PKM**), respectively. Although these coproducts contain less protein (usually between 14 and 22%) than other oilseed meals, they represent the largest quantity of locally available feed protein in many tropical countries (Creswell and Brooks, 1971; Ravindran and Blair, 1992). Copra and palm kernel products are, therefore, often fed to pigs in Latin America, Africa, and Asia, but there are limited data on the nutritional value of copra and palm kernel ingredients. Although values for DE and ME and apparent and standardized ileal digestibility of AA in these ingredients were recently reported (Sulabo et al., 2013), there are very few data on the digestibility of P in copra and palm kernel products.

Copra and palm kernel ingredients contain between 0.50 and 0.60% total P (Sauvant et al., 2004), which is more than corn but less than soybean meal (**SBM**). As with other plant ingredients, some of the P in copra and

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Table 1. Analyzed nutrient composition of ingredients (as-fed basis)[1]

	Ingredient				
Item	CM	PKE-IN	PKE-CR	PKM	SBM
DM, %	90.54	89.29	91.45	89.51	86.09
CP (N × 6.25), %	21.99	14.25	14.41	13.58	47.01
ADF, %	26.89	41.88	44.07	49.40	4.17
NDF, %	54.76	68.51	72.63	77.86	6.94
Ash, %	5.96	3.95	3.82	3.77	5.97
Ca, %	0.04	0.36	0.26	0.20	0.26
Total P, %	0.52	0.51	0.53	0.54	0.67
Phytic acid, %	0.79	1.24	1.34	1.12	1.55
Phytate P,[2] %	0.22	0.35	0.38	0.32	0.44
Nonphytate P,[3] %	0.30	0.16	0.15	0.22	0.23
Phytase, units/kg	94	170	130	160	81

[1]CM = copra meal (Stance Global, Pty Ltd.., Chapel Hill, QLD, Australia); PKE-IN = palm kernel expellers from Indonesia (PPC Logistics, Oakland CA); PKE-CR = palm kernel expellers from Costa Rica (Unimar, San José, Costa Rica); PKM = palm kernel meal from Costa Rica (Industrial de Oleaginosas Americanas S. A., Puntarenas, Costa Rica); SBM = soybean meal.

[2]Calculated as 28.2% of phytic acid (Tran and Sauvant, 2004).

[3]Calculated as total P – phytate P.

palm kernel ingredients is bound to phytate (Eeckhout and De Paepe, 1994). However, the standardized total tract digestibility (**STTD**) of P in copra and palm kernel ingredients fed to pigs has not been determined and the effect of microbial phytase on the STTD of P in copra and palm kernel ingredients has not been reported. Therefore, the objective of this experiment was to determine the effect of microbial phytase on the STTD of P in CM, PKE, and PKM fed to growing pigs and to compare these values to those determined for SBM.

MATERIALS AND METHODS

The experimental protocol was reviewed and approved by the Institutional Animal Care and Use Committee of the University of Illinois.

General

Pigs used in the experiment were the offspring of G-Performer boars that were mated to Fertilium 25 females (Genetiporc, Alexandria, MN). Copra meal was obtained from Stance Global, Pty Ltd., Chapel Hill, Australia. Palm kernel expellers were sourced from a palm oil plant in Indonesia (palm kernel expellers from Indonesia [**PKE-IN**]) and also from Unimar, San José, Costa Rica (palm kernel expellers from Costa Rica [**PKE-CR**]). Palm kernel meal was produced by and obtained from Industrial de Oleaginosas Americanas S. A., Puntarenas, Costa Rica. The same batches of CM, PKM, PKE-IN, and PKE-CR that were used by Sulabo et al. (2013) were also used in this experiment (Table 1).

Table 2. Ingredient composition of experimental diets (%; as-fed basis)[1,2]

	Diet					
Item	CM	PKE-IN	PKE-CR	PKM	SBM	P free
CM	35.00	–	–	–	–	–
PKE-IN	–	35.00	–	–	–	–
PKE-CR	–	–	35.00		–	–
PKM	–	–	–	35.00		–
SBM (47% CP)	–	–	–	–	30.00	–
Gelatin[3]	–	–	–	–	–	20.00
Cornstarch	45.30	45.50	45.50	45.50	50.50	49.22
Sucrose	15.00	15.00	15.00	15.00	15.00	20.00
Soybean oil	3.00	3.00	3.00	3.00	3.00	4.00
Solka-floc[4]	–	–	–	–	–	4.00
Ground limestone	1.00	0.80	0.80	0.80	0.80	0.80
AA mixture[5]	–	–	–	–	–	0.78
Salt	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin–mineral premix[6]	0.30	0.30	0.30	0.30	0.30	0.30
Potassium carbonate	–	–	–	–	–	0.40
Magnesium oxide	–	–	–	–	–	0.10
Total		100.00	100.00	100.00	100.00	100.00

[1]CM = copra meal (Stance Global, Pty Ltd., Chapel Hill, QLD, Australia); PKE-IN = palm kernel expellers from Indonesia (PPC Logistics, Oakland CA); PKE-CR = palm kernel expellers from Costa Rica (Unimar, San José, Costa Rica); PKM = palm kernel meal from Costa Rica (Industrial de Oleaginosas Americanas S. A., Puntarenas, Costa Rica); SBM = soybean meal.

[2]Five additional diets formulated were similar to CM, PKE-IN, PKE-CR, PKM, and SBM, respectively, with the exception that 0.04% OptiPhos 2000 (2,000 phytase units/g; Enzyvia, Sheridan, IN) was included in each of these diets at the expense of cornstarch.

[3]Pork gelatin obtained from Gelita Gelatine USA Inc. (Sioux City, IA).

[4]Fiber Sales and Development Corp. (Urbana, OH).

[5]Provided the following quantities (%) of AA: DL-Met, 0.27; L-Thr, 0.08; L-Trp, 0.14; L-His, 0.08; L-Ile, 0.16; and L-Val, 0.05.

[6]Provided the following quantities of vitamins and minerals 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.

Animals, Diets, and Experimental Design

Sixty-six growing barrows (initial BW: 27.4 ± 2.8 kg) were randomly allotted to 11 dietary treatments using a generalized randomized block design with 3 blocks of 22 pigs and 6 replicate pigs per diet. Pigs were placed in metabolism cages that allowed for total collection of feces. Each metabolism cage was equipped with a feeder and a nipple drinker and a screen floor was placed under the slatted floors of the cages, which allowed for quantitative collection of feces.

Eleven diets were formulated (Tables 2 and 3). Five diets were formulated by mixing cornstarch and sugar with CM, PKE-IN, PKE-CR, PKM, or SBM. Five addi-

Table 3. Analyzed composition of experimental diets (as-fed basis)[1]

	Diet										
	CM		PKE-IN		PKE-CR		PKM		SBM		
Item FTU[2]/kg:	0	800	0	800	0	800	0	800	0	800	P free
DM, %	92.0	92.3	90.9	91.8	92.4	92.6	91.8	91.6	91.1	90.1	92.3
ADF, %	9.45	9.89	12.82	14.13	14.81	16.60	18.16	18.70	0.91	1.25	3.15
NDF, %	20.98	19.66	39.18	26.50	24.71	26.93	28.82	28.74	2.50	2.25	3.58
Ash, %	3.49	3.42	2.69	2.84	2.84	2.53	2.56	3.04	3.15	3.21	2.08
Total P, %	0.20	0.21	0.19	0.20	0.19	0.20	0.22	0.21	0.23	0.22	0.02
Ca, %	0.41	0.46	0.52	0.48	0.45	0.40	0.50	0.40	0.39	0.38	0.36
Phytase, FTU/kg	<60	1,100	110	850	<60	1,200	110	960	<60	1,100	–

[1]CM = copra meal (Stance Global, Pty Ltd., Chapel Hill, QLD, Australia); PKE-IN = palm kernel expellers from Indonesia (PPC Logistics, Oakland CA); PKE-CR = palm kernel expellers from Costa Rica (Unimar, San José, Costa Rica); PKM = palm kernel meal from Costa Rica (Industrial de Oleaginosas Americanas S. A., Puntarenas, Costa Rica); SBM = soybean meal.

[2]FTU = phytase unit.

tional diets, which were identical to the initial 5 diets but supplemented with 800 units of phytase (OptiPhos 2000; Enzyvia, Sheridan, IN), were also prepared. The last diet was a P-free diet used to measure the basal endogenous P loss (**EPL**). Vitamins and all minerals, except P and Ca, were included in the diets according to requirements for growing pigs (NRC, 1998).

Pigs were fed at a level of 2.5 times their estimated maintenance energy requirement (i.e., 106 kcal ME/kg$^{0.75}$; NRC, 1998) and the daily feed allotments were divided into 2 equal meals. Water was available at all times. Pigs were fed their experimental diets for 12 d. The initial 5 d were considered an adaptation period to the diet. Feces were collected from d 6 to 11 according to the marker to marker approach (Adeola, 2001). Fecal samples were stored at –20°C immediately after collection.

Chemical Analyses

Fecal samples were dried in a forced-air oven and finely ground before being analyzed. Ingredients, diets, and feces were analyzed for DM by oven drying duplicate samples at 135°C for 2 h (method 930.15; AOAC Int., 2007). Calcium and total P in these samples were analyzed by the inductively coupled plasma spectroscopy method (method 985.01 A, B, and C; AOAC Int., 2007) after wet ash sample preparation (method 975.03 B(b); AOAC Int., 2007). The concentration of N in ingredient and diet samples was determined using the combustion procedure (method 990.03; AOAC Int., 2007) with a rapid N-cube protein/nitrogen apparatus (Elementar Americas Inc., Mt. Laurel, NJ). Aspartic acid was used as a calibration standard and CP was calculated as N × 6.25. Diets and ingredients were also analyzed for ADF (method 973.18; AOAC Int., 2007), NDF (Holst, 1973), and dry ash (method 942.05; AOAC Int., 2007). Ingredients were analyzed for phytic acid concentration (Ellis et al., 1977), and both ingredients and diets were analyzed for phytase activity (Phytex Method, version 1; Eurofins, Des Moines, IA).

Calculations and Data Analyses

The apparent total tract digestibility (**ATTD**) of P and the STTD of P in each of the 10 P-containing diets were calculated (Almeida and Stein, 2010). The basal EPL was also calculated according to Almeida and Stein (2010). The test ingredients were the only source of P in each diet and the calculated ATTD and STTD values of P in the diets, therefore, also represent the ATTD and STTD of P in the ingredients. The ATTD of Ca was also calculated for each diet.

Normality of data was confirmed and outliers were tested using the UNIVARIATE procedure (SAS Inst. Inc., Cary, NC), but no outliers were detected. Data were analyzed using the MIXED procedure of SAS with pig as the experimental unit. The model included diet, phytase, and diet × phytase as fixed effects and block as the random effect. Least squares means were calculated for each independent variable. Simple linear regressions were performed using PROC REG in SAS and the concentration of phytate P in the ingredients (expressed as a percentage of total P) were used to calculate the effects of phytic acid on the ATTD and STTD of P. The α-level used to determine significance among means was 0.05.

RESULTS

Composition of Ingredients

Soybean meal contained 47.01% CP and the concentrations of CP in CM, PKE-IN, PKE-CR, and PKM were 21.99, 14.25, 14.41, and 13.58%, respectively (Table 1). However, the concentrations of ADF and NDF in CM, PKE-IN, PKE-CR, and PKM were 26.89 and 54.76%, 41.88 and 68.51%, 44.07 and 72.63%, and 49.40 and 77.86%, respectively, whereas SBM contained 4.17%

Table 4. Effects of phytase on P balance, apparent total tract digestibility (ATTD), and standardized total tract digestibility (STTD) of P in copra meal (CM), palm kernel expellers from Indonesia (PKE-IN), palm kernel expellers from Costa Rica (PKE-CR), palm kernel meal from Costa Rica (PKM), and soybean meal (SBM) fed to growing pigs[1,2]

	Diet											*P*-value		
	CM		PKE-IN		PKE-CR		PKM		SBM					
Item FTU/kg:	0	800	0	800	0	800	0	800	0	800	SEM	Diet	Phytase	Diet × phytase
ADFI, g/d	760	787	807	800	891	935	833	832	795	796	43	0.02	0.64	0.97
P intake, g/d	1.65	1.79	1.69	1.75	1.83	2.02	2.00	1.91	2.01	1.94	0.09	0.01	0.45	0.52
Fecal output, g/d	50.0	45.8	97.5	92.2	112.1	121.3	99.9	100.2	29.3	25.1	9.6	<0.01	0.88	0.94
P in feces, %	1.35	0.75	1.21	0.81	1.10	0.67	1.02	0.69	3.96	2.16	0.06	<0.01	<0.01	<0.01
P output, g/d	0.68	0.34	1.15	0.75	1.24	0.82	1.01	0.69	1.18	0.54	0.11	<0.01	<0.01	0.61
P absorption, g/d	0.97	1.45	0.54	1.00	0.60	1.20	0.99	1.23	0.83	1.41	0.13	<0.01	<0.01	0.65
ATTD of P, %	60.6	80.8	27.3	56.5	32.6	59.9	48.9	64.1	41.1	72.2	6.7	<0.01	<0.01	0.74
Basal EPL,[3] mg/d	164	170	174	173	193	202	180	180	172	172	9	0.02	0.63	0.97
STTD of P,[4] %	70.6	90.3	37.6	66.4	43.2	69.9	57.9	73.5	49.6	81.1	6.7	<0.01	<0.01	0.75

[1]Phytase: OptiPhos 2000 (2,000 phytase unit [FTU]/g; Enzyvia, Sheridan, IN).

[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 216 ± 70 mg/kg DMI. The daily basal EPL (mg/d) for each diet was calculated by multiplying the EPL (mg/kg DMI) by the daily DMI of each diet (Almeida and Stein, 2010).

[4]Values for STTD were calculated by correcting values of ATTD for basal endogenous losses (NRC, 2012).

ADF and 6.94% NDF. The concentrations of ash in CM, PKE-IN, PKE-CR, PKM, and SBM were 5.96, 3.95, 3.82, 3.77, and 5.97%, respectively, and the concentrations of Ca in CM, PKE-IN, PKE-CR, PKM, and SBM were 0.04, 0.36, 0.26, 0.20, and 0.26%, respectively. The concentration of P in CM and all the palm kernel ingredients was between 0.51 and 0.54%, but SBM contained 0.67% P. The concentrations of phytate-bound and non-phytate-bound P were 0.22 and 0.30% in CM, 0.35 and 0.16% in PKE-IN, 0.38 and 0.15% in PKE-CR, 0.32 and 0.22% in PKM, and 0.44 and 0.23% in SBM, respectively. Copra meal and the palm kernel ingredients had intrinsic phytase activity ranging from 94 to 170 phytase units (**FTU**)/kg and the phytase activity in SBM was 81 FTU/kg.

Phosphorus Digestibility

There was no diet × phytase interaction for any of the response variables measured except for the concentration of P in feces ($P < 0.01$; Table 4). Average daily feed intake of pigs fed PKE-CR was greater ($P < 0.05$) than for pigs fed PKE-IN, CM, or SBM, but ADFI of pigs fed PKM was not different from that of pigs fed any of the other ingredients. Pigs fed SBM, PKM, or PKE-CR had greater ($P < 0.05$) daily P intake compared with pigs fed CM or PKE-IN. Pigs fed SBM had less ($P < 0.05$) daily fecal output than pigs fed CM, but pigs fed SBM and CM had less ($P < 0.05$) daily fecal output than pigs fed PKE-IN, PKM, or PKE-CR. Regardless of phytase addition, there was greater ($P < 0.05$) concentration of P in the feces of pigs fed SBM compared with the feces of pigs fed CM, PKE-IN, PKE-CR, or PKM. No differences in fecal P concentrations were observed among pigs fed CM or the palm kernel products when phytase was added to the diet; however, pigs fed CM had greater ($P < 0.05$) fecal P concentration than pigs fed PKE-CR or PKM without added phytase. Daily fecal P output was less ($P < 0.05$) for pigs fed CM compared with pigs fed all other diets. The daily amount of P absorbed by pigs fed CM was greater ($P < 0.05$) compared with pigs fed PKE-CR or PKE-IN. The daily amount of P absorbed by pigs fed SBM and PKM were not different from that of pigs fed CM or PKE-CR but greater ($P < 0.05$) than for pigs fed PKE-IN.

The ATTD of P in CM was greater ($P < 0.05$) than that for any of the other ingredients. The ATTD of P in SBM and PKM was greater ($P < 0.05$) than in PKE-IN, with PKE-CR being intermediate. The basal EPL was estimated at 216 ± 70 mg/kg DMI. The daily EPL in PKE-CR was greater ($P < 0.05$) than in PKE-IN, SBM, or CM, with PKM being intermediate. The STTD of P in CM was greater ($P < 0.05$) than in all other ingredients. The STTD of P in PKM was also greater ($P < 0.05$) than in PKE-IN, with SBM and PKE-CR being intermediate.

There was a negative linear relationship ($P < 0.05$; Fig. 1) between the concentration of phytate P in the ingredients (expressed as a percentage of total P) and the ATTD of P (107.09 – 1.0564 × % phytate P; $R^2 = 87.1$) and STTD of P (116.3 – 1.0487 × % phytate P; $R^2 = 89.4$).

Addition of phytase to the diet did not affect ADFI, daily fecal output, or daily P intake. However, pigs fed diets with phytase had less ($P < 0.01$) daily fecal P output but greater ($P < 0.01$) daily amount of P absorbed compared with pigs fed diets with no phytase. Addition of phytase also increased ($P < 0.05$) the ATTD and STTD of P. There was no effect of phytase addition on daily EPL.

Table 5. Effects of phytase on Ca balance and apparent total tract digestibility (ATTD) of Ca in diets containing copra meal (CM), palm kernel expellers from Indonesia (PKE-IN), palm kernel expellers from Costa Rica (PKE-CR), palm kernel meal from Costa Rica (PKM), and soybean meal (SBM) fed to growing pigs[1,2]

	Diet													
	CM		PKE-IN		PKE-CR		PKM		SBM			*P*-value		
Item FTU/kg:	0	800	0	800	0	800	0	800	0	800	SEM	Diet	Phytase	Diet × phytase
Ca intake, g/d	3.12	3.62	4.20	3.84	4.01	3.74	4.17	3.33	3.10	3.02	0.18	<0.01	0.11	<0.05
Ca in feces, %	1.78	1.13	1.95	1.25	1.09	0.94	0.78	0.55	4.68	3.25	0.19	<0.01	<0.01	0.02
Ca output, g/d	0.92	0.56	1.80	1.23	1.20	1.21	0.79	0.55	1.38	0.80	0.18	<0.01	<0.01	0.48
Ca absorption, g/d	2.19	3.07	2.69	2.61	2.82	2.53	3.38	2.78	1.73	2.23	0.21	<0.01	0.53	<0.01
ATTD of Ca, %	71.7	85.0	59.2	68.7	70.1	68.5	80.7	83.5	55.2	73.4	4.8	<0.01	<0.01	0.25

[1]Phytase: OptiPhos 2000 (2,000 phytase unit [FTU]/g; Enzyvia, Sheridan, IN).

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

Calcium Digestibility

There were diet × phytase interactions ($P < 0.05$) for daily Ca intake, fecal Ca concentration, and daily amount of Ca absorbed (Table 5). When phytase was not added to the diet, daily Ca intake was greater in pigs fed diets containing the palm kernel ingredients compared with pigs fed diets containing CM or SBM. When phytase was included in the diet, pigs fed CM, PKE-IN, and PKE-CR had greater daily Ca intake than pigs fed SBM. Regardless of phytase addition, fecal Ca concentration was greater ($P < 0.05$) for pigs fed SBM than for pigs fed CM or the palm kernel ingredients. The concentration of Ca in feces was also greater ($P < 0.05$) for pigs fed PKE-IN or CM compared with pigs fed diets containing PKE-CR or PKM without phytase. However, pigs fed PKE-IN or CM with phytase had fecal Ca concentration that was not different from that of pigs fed PKE-CR with phytase but greater ($P < 0.05$) than that of pigs fed PKM with phytase. There was no diet × phytase interaction for daily fecal Ca output. Pigs fed PKE-IN had greater ($P < 0.05$) daily fecal Ca output compared with pigs fed SBM, CM, or PKM. Pigs fed PKE-CR also had greater ($P < 0.05$) daily fecal Ca output than pigs fed CM or PKM, whereas daily fecal Ca output was greater ($P < 0.05$) for pigs fed SBM than for pigs fed PKM. Daily fecal Ca output was reduced ($P < 0.01$) when phytase was added to the diet. When phytase was not added to the diets, pigs fed PKM absorbed more ($P < 0.05$) Ca than pigs fed PKE-IN, CM, or SBM, and pigs fed PKE-CR also had greater ($P < 0.05$) Ca absorption than pigs fed CM or SBM, and pigs fed PKE-IN had greater ($P < 0.05$) Ca absorption than pigs fed SBM. When phytase was added to the diets, pigs fed CM and PKM had greater ($P < 0.05$) Ca absorption compared with pigs fed SBM. There was no diet × phytase interaction for ATTD of Ca in the diet. Regardless of phytase addition, diets containing PKM had ATTD of Ca that was not different from that of diets containing CM but greater ($P < 0.05$) than the ATTD for diets containing PKE-CR, SBM, or PKE-IN. Likewise, diets containing CM had greater ($P < 0.05$) ATTD of Ca compared with diets containing SBM or PKE-IN. On average, the addition of phytase improved ($P < 0.01$) the ATTD of Ca from 67.4 to 75.8%.

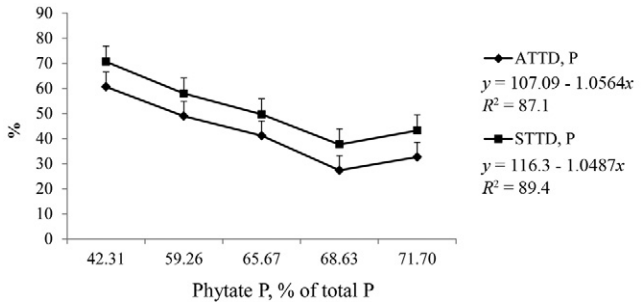

Figure 1. The negative linear relationship ($P < 0.05$) between the concentration of phytate P in the ingredients (expressed as a percentage of total P) and the apparent total tract digestibility (ATTD) or standardized total tract digestibility (STTD) of P.

DISCUSSION

Composition of Ingredients

The values for ash, total P, and Ca in SBM concur with published values (NRC, 1998; Sauvant et al., 2004). The concentration of ash, P, and Ca in CM also agree with previous reports (Creswell and Brooks, 1971; Lekule et al., 1990; NRC, 1998; O'Doherty and McKeon, 2000; Kim et al., 2001; Sauvant et al., 2004; PHILSAN, 2011). The concentrations of ash, total P, and Ca in PKE-IN, PKE-CR, and PKM also are within the range of previously published data for palm kernel ingredients (Babatunde et al., 1975; Agunbiade et al., 1999; Kim et al., 2001; Février et al., 2001; Sauvant et al., 2004; Ezieshi and Olomu, 2007; PHILSAN, 2011). These observations indicate that the oil seed meals used in this experiment contained the same quantities of ash, Ca, and P as meals used in previous experiments. However, CM is a poor source of Ca

compared with other oil seed meals, and therefore, use of feed ingredients high in Ca or supplementation with limestone is necessary if CM is used in swine diets.

Published values for phytate P in SBM, CM, and PKE range from 0.37 to 0.40, 0.14 to 0.20, and 0.33 to 0.41%, respectively, on an as-fed basis (Eeckhout and De Paepe, 1994) and the data obtained in this experiment are within these ranges. The phytase activity of SBM (83 FTU/kg) measured in this study agree with previous values (0 to 149 FTU/kg), whereas the phytase activity in CM (91 FTU/kg) and the palm kernel ingredients (125 to 168 FTU/kg) were slightly greater than the range of values reported by Eeckhout and De Paepe (1994). The differences in phytate P concentration and intrinsic phytase activity may be due to differences in cultivars, processing conditions, or the analytical procedures used.

Phosphorus Digestibility

The digestibility of P in feed ingredients may be measured using balance studies, which indirectly estimate P availability by measuring digestive utilization (Fan et al., 2001). However, ATTD values of P of individual feed ingredients are not always additive in mixed diets (Fan and Sauer, 2002). This may be due to endogenous P output, which potentially complicates estimates of apparent P digestibility. When ATTD of P in feedstuffs is corrected for basal EPL, the STTD of P is determined (NRC, 2012), and values for STTD of P are more additive in mixed diets than values for ATTD of P (Almeida and Stein, 2010; NRC, 2012).

The ATTD and STTD of P in SBM obtained in this experiment agree with published values (Almeida and Stein, 2010; Kim and Stein, 2010; Goebel and Stein, 2011). There are limited data on the ATTD of P in PKE, and to our knowledge, there are no published values for CM and PKM. The ATTD of P in copra expellers is 31 to 34% (Jongbloed and Kemme, 1990; Sauvant et al., 2004), but the results of the present experiment indicate that the ATTD of P in CM is much greater. In contrast, the ATTD of P in the 2 sources of PKE that were determined in the present experiment (28 and 31%) are in agreement with the value of 31% reported by Sauvant et al. (2004).

The basal EPL that was estimated in this experiment (216 ± 70 mg per kg DMI) is in very good agreement with values reported by Stein et al. (2006), Widmer et al. (2007), and Almeida and Stein (2010), and also close to the value (190 mg/kg DMI) estimated by NRC (2012). To our knowledge, the STTD of P in CM, PKE, and PKM have not been previously reported. The STTD of P in CM (70.6%) was similar to the STTD of P in corn distillers dried grains with solubles (72.9%; Almeida and Stein, 2010), but greater than in corn (26.4%; Almeida and Stein, 2010) and SBM (48.3 to 56.7%; Almeida and Stein, 2010; Kim and Stein, 2010).

The differences in P digestibility within and between oilseed meals may be explained by differences in the concentrations of phytate P. When expressed as a percentage of total P, phytate P concentration in the feed ingredients used in this experiment explained 87.1 and 89.4% of the variability in ATTD and STTD of P, respectively, and there was a strong negative relationship between ATTD or STTD of P and the concentration of phytate P. Copra meal had the least phytate P concentration (42%) among ingredients used in this experiment. Phytate P concentration in copra expellers ranges from 30 to 39% (Eeckhout and De Paepe, 1994), but we are not aware of other values for CM. The negative relationship between phytate P and P digestibility indicates that phytate P concentration may be used as a predictor of STTD of P in the ingredients used in this experiment.

As expected, addition of exogenous phytase to the diet increased the ATTD and STTD of P in all ingredients. Because phytate P is poorly digested by pigs, addition of exogenous phytase to hydrolyze the phytate bond and subsequently improve P digestibility is a common industry practice (Sands et al., 2001; Kies et al., 2006). Therefore, adding phytase to diets containing copra and palm kernel ingredients improves P digestibility and will reduce the need for inorganic phosphates in the diets.

Calcium Digestibility

The diets used in this experiment contained 0.38 to 0.52% Ca, which is 58 to 79% of the Ca requirement (0.66%) for 25- to 50-kg pigs (NRC, 2012). This indicates that all the experimental diets provided Ca below the pigs' requirement. However, previous studies have demonstrated that the ATTD of Ca in diets is not affected by the dietary content of Ca (Pointillart et al., 1989; Stein et al., 2011), whereas excess Ca in the diets will reduce P digestibility (Stein et al., 2011). All diets contained 0.80% limestone except for the CM diet, which contained 1.0% limestone because of the very low Ca content in CM. Assuming that limestone contains 36% Ca (NRC, 1998), 55 to 88% of the Ca in the diets was contributed by limestone, with the remaining Ca originating from the plant ingredients. Therefore, the ATTD of Ca in the diets represents the ATTD of a combination of Ca from limestone and Ca from the plant ingredients.

The observed differences in the ATTD of Ca among diets may be related to differences in the contribution of limestone to the total Ca of the diets and the phytate concentration of the ingredients. The ATTD of Ca in the CM diet (71.7%) fed to pigs, in which limestone contributed 88% of the total Ca, was similar to values obtained in a wheat–barley–corn-based diet containing

limestone that contributed 86% of the Ca (63 to 74%; Malde et al., 2010). In previous studies, the ATTD of Ca in SBM and limestone was estimated at 46.7 and 61 to 71%, respectively (Bohlke et al., 2005; Stein et al., 2011). The greater phytate concentration in SBM and the PKE may explain the lower digestibility of Ca in these diets compared with the PKM diet. Phytic acid has the ability to form Ca-phytate complexes, which renders Ca unavailable for absorption (Sandberg et al., 1993; Saha et al., 1994). Adding phytase to the diets improves Ca utilization in pigs (Lei et al., 1993; Brady et al., 2002; Jendza et al., 2006; Guggenbuhl et al., 2007), which may be due to increased release of Ca during the breakdown of Ca-phytate complexes in the gut (Selle et al., 2009). There was, however, an inconsistent effect of phytase on ATTD of Ca in this experiment, and it appears that the ability of microbial phytase to release Ca from the phytate complex may be dependent on the diet.

In conclusion, data from this experiment indicate that CM has greater STTD of P than PKE, PKM, and SBM fed to growing pigs. The relatively high STTD of P in CM indicates that the inclusion of inorganic P can be reduced if CM is included in diets fed to pigs and excretion of P can be reduced. The addition of phytase improves the STTD of P in all the ingredients used in this experiment, which may reduce the use of inorganic phosphates in swine diets and further reduce the excretion of P in the feces.

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