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Non Ruminant Nutrition

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Effects of standardized total tract digestible phosphorus on growth performance of 11- to 23-kg pigs fed diets with or without phytase[1,2]

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Abstract

Two experiments were conducted to determine the standardized total tract digestible phosphorus (**STTD P**) requirement for 11- to 23-kg nursery pigs fed diets with or without phytase. A total of 1,080 and 2,140 pigs (PIC 359 × Camborough, Hendersonville, TN; initially 11.4 ± 0.29 and 11.1 ± 0.24 kg) were used in Exp. 1 and Exp. 2, respectively. There were 23 to 27 pigs per pen with 6 and 12 replicate pens per treatment in Exp. 1 and Exp. 2, respectively. After weaning, pigs were fed a common pelleted diet with 0.45% STTD P for 7 d, and a common phase 2 meal diet with 0.40% STTD P for 14 d in Exp. 1 and 18 d in Exp. 2. Pens of pigs were then allotted to dietary treatments in a randomized complete block design with body weight (BW) as the blocking factor. In Exp. 1, dietary treatments consisted of 0.26%, 0.30%, 0.33%, 0.38%, 0.43%, 0.48%, and 0.53% STTD P. Treatments were achieved with the inclusion of monocalcium phosphate at the expense of corn. In Exp. 2, diets contained 1,000 phytase units (**FYT;** Ronozyme Hiphos 2500, DSM Nutritional Products, Inc., Parsippany, NJ) with assumed release value 0.132% STTD P, and treatments consisted of 0.30%, 0.33%, 0.38%, 0.43%, 0.48%, 0.53%, and 0.58% STTD P. These STTD P concentrations included the expected phytase release of 0.132% STTD P. In both experiments, a similar 1.17:1 Ca:P ratio was maintained across treatments. Statistical models included linear model (**LM**), quadratic polynomial (**QP**), broken-line linear (**BLL**), and broken-line quadratic (**BLQ**). In Exp. 1, increasing STTD P increased (linear, $P < 0.001$) ADG, ADFI, G:F, final BW, and grams of STTD P intake per day and per kilogram of gain. There was also a marginal quadratic response for G:F ($P < 0.066$). In Exp. 2, ADG and G:F increased quadratically ($P < 0.05$), whereas ADFI increased linearly ($P = 0.060$) with increasing STTD P. The BLL and QP model provided similar fit to G:F in Exp. 1, estimating the requirement for maximum G:F at 0.34% and 0.42%, respectively. The BLL was the best fitting model for ADG and G:F in Exp. 2, estimating the breakpoint at 0.40% and 0.37% STTD P, respectively. The BLL and BLQ models estimated the breakpoint for ADG as a function of STTD P intake in grams per day at 2.92 and 3.02 g/d, respectively. These data provide empirical evidence that for 11- to 23-kg pigs, the NRC (2012) accurately estimates the STTD P requirement on a g/d basis. As a percentage of the diet, the STTD P requirement for diets without or with 1,000 FYT added phytase ranged from 0.34% to 0.42%.

Key words: growth, modeling, nursery pigs, phosphorus requirement, phytase

Introduction

Phosphorus (**P**) is the second most abundant mineral in the body after calcium (**Ca**) and is required for multiple biological functions (Berndt and Kumar, 2009). However, P concentration can greatly affect dietary cost as P is considered the third most expensive nutrient in swine diets. Thus, driven by economic and environmental concerns, P supplementation is typically associated with lower safety margins in swine diets compared with Ca (Crenshaw, 2001).

The NRC (2012) reports the P requirement estimates by pigs on a standardized total tract digestible (**STTD**) basis. The requirement estimates of STTD P for pigs weighing less than 20 kg of BW, however, were derived from a simple mathematical regression model that includes a limited number of published empirical studies. There is a need for more empirical data to validate the NRC estimates. In fact, recent research suggests that the NRC (2012) requirement estimates may underestimate the P concentration needed to optimize pig growth performance (Zhai and Adeola, 2013; Adeola et al., 2015; Wu et al., 2018). Thus, it is important to reassess the STTD P requirement of growing pigs in commercial pig production.

Approximately 60% to 80% of P in feedstuffs of plant origin is stored in phytic acid (Eeckhout and De Paepe, 1994). Pigs poorly utilize the phytate-bound-P because they lack sufficient endogenous phytase to effectively cleave the phosphates from the phytate. Thus, practical nursery diets are typically formulated with added phytase to increase P availability to the pig while decreasing the need for expensive inorganic sources of P (Selle and Ravindran, 2008).

We hypothesized that the STTD P requirements would be similar for pigs fed diets with and without the inclusion of phytase, given the P release values from the phytase are correct. To the best of our knowledge, empirical data determining the STTD P requirement of nursery pigs with and without phytase are limited. Therefore, the objective of our study was to determine the effects of increasing STTD P concentration while maintaining a similar Ca:P ratio in diets with or without phytase (1,000 phytase units; **FYT**) on growth performance of 11- to 23-kg pigs housed under commercial conditions.

Material and Methods

The Kansas State University Institutional Animal Care and Use Committee (Manhattan, KS) approved all experimental procedures in this study.

Animals and Diets

Two studies were conducted at a commercial research-nursery site in southwestern Minnesota (New Horizon Farms, Pipestone, MN). The facility was environmentally controlled and mechanically ventilated. Two rooms were used, each containing 42 pens (3.70 × 2.30 m^2) with completely slatted flooring and a deep pit for manure storage. Each pen was equipped with a 5-hole stainless steel dry self-feeder (SDI Industries, Alexandria, SD) and a pan waterer. The facilities were equipped with a computerized feeding system (FeedPro; Feedlogic Corp., Willmar, MN) capable of blending and distributing diets to each pen as specified. Furthermore, the system can measure and record daily feed additions to individual pens. At placement in the nursery, barrows and gilts (PIC 359 × Camborough, Genus PIC, Hendersonville, TN) were balanced by sex and allowed ad libitum access to feed and water throughout the experiments.

A total of 1,080 pigs (initial average BW of 11.4 ± 0.29 kg) in Exp. 1 and 2,140 pigs (initial average BW of 11.1 ± 0.24 kg) in Exp. 2 were used in two 21-d growth trials. Pigs in Exp. 1 were weaned at approximately 21 d of age and pigs in Exp. 2 were weaned at approximately 19 d of age. A common phase 1 pelleted diet was fed for 7 d in both trials, and a common phase 2 meal diet was fed for 14 or 18 d in Exp. 1 and Exp. 2, respectively. Both common diets were formulated to be at the pigs' STTD P requirement based on the NRC estimates (0.45% and 0.40% STTD P, respectively). At day 0 of the trial, pens of pigs were allotted to dietary treatments in a randomized complete block design with BW as the blocking factor. There were 6 replicate pens per treatment with 23 to 27 pigs (similar numbers of barrows and gilts) per pen in Exp. 1, and 12 replicate pens per treatment with 24 to 27 pigs (similar numbers of barrows and gilts) per pen in Exp. 2.

All treatment diets were manufactured at the New Horizon Farms Feed Mill in Pipestone, MN and fed in meal form. In Exp. 1, 2 experimental corn-soybean meal–based diets were formulated (Table 1) to contain 0.26% and 0.53% STTD P and then were blended using the robotic feeding system to create the intermediate STTD P levels. The STTD P levels were achieved by increasing the addition of limestone and monocalcium phosphate at the expense of corn, with no added phytase. The NRC (2012) suggested a total Ca:P ratio between 1.10 and 1.25:1. Therefore, a similar 1.17:1 to 1.18:1 total Ca:P ratio was maintained across dietary treatments. The percentage of low and high STTD P diet blended to create the treatment diets were 100:0, 88:12, 75:25, 56:44, 37:63, 19:81, and 0:100 to achieve 0.26%, 0.30%, 0.33%, 0.38%, 0.43%, 0.48%, and 0.53% STTD P, respectively. The NRC (2012) requirement estimate for nursery pigs from 11- to 23-kg, expressed as a percentage of the diet, is 0.33% STTD P. Therefore, treatment concentrations represented 80%, 90%, 100%, 115%, 130%, 145%, and 160% of the NRC requirement estimate.

In Exp. 2, 2 experimental corn-soybean meal–based diets were formulated (Table 1) to contain 0.30% and 0.58% STTD P and then were blended using the robotic feeding system to create the intermediate STTD P levels. The diets contained 1,000 FYT of Ronozyme Hiphos 2500 (DSM Nutritional Products, Inc., Parsippany, NJ) with assumed release values of 0.15% available P and 0.132% STTD P. The STTD P levels were achieved by increasing the amount of limestone and monocalcium phosphate at the expense of corn. A similar 1.17:1 Ca:P ratio was maintained across dietary treatments. The percentage of low and high STTD P diet blended to create the treatment diets were 100:0, 89:11, 71:29, 53:47, 36:64, 18:82, and 0:100 to achieve 0.30%, 0.33%, 0.38%, 0.43%, 0.48%, 0.53%, and 0.58% STTD P, respectively. These STTD P concentrations included the expected phytase release of 0.132% STTD P. The treatment concentrations represented 90%, 100%, 115%, 130%, 145%, 160%, and 175% of the NRC requirement. The lowest STTD P diet did not contain any monocalcium phosphate. Thus, the STTD P was entirely from corn, soybean meal, and the P liberated by phytase.

Pigs were weighed and feed disappearance was measured on days 0 and 21 in both experiments to determine ADG, ADFI, G:F ratio, grams of STTD P intake per day, and grams of STTD P intake per kilogram of gain. The STTD P, based on formulated values, were multiplied by ADFI to calculate grams of STTD P intake per day. The total grams of STTD P intake, based on formulated values, were divided by total BW gain to calculate the grams of STTD P intake per kilogram of gain.

Table 1. Diet composition, Exp. 1 and 2 (as-fed basis)[1]

Item	Exp. 1		Exp. 2	
	0.26% STTD P[2]	0.53% STTD P	0.30% STTD P	0.58% STTD P
Ingredients, %				
Corn	64.95	63.10	65.79	63.73
Soybean meal, 46,5% CP	31.72	31.85	31.66	31.80
Monocalcium phosphate, 21% P	0.52	1.92	0.00	1.60
Limestone	1.00	1.30	0.74	1.05
Sodium chloride	0.60	0.60	0.65	0.65
L-Lysine HCl	0.48	0.48	0.48	0.48
DL-Methionine	0.21	0.21	0.21	0.21
L-Threonine	0.16	0.16	0.16	0.16
L-Tryptophan	0.03	0.03	0.03	0.03
L-Valine	0.08	0.08	0.08	0.08
Phytase[3]	–	–	0.04	0.04
Vitamin premix[4]	0.13	0.13	–	–
Trace mineral premix[5]	0.10	0.10	–	–
Vitamin and trace mineral premix[6]	–	–	0.15	0.15
Copper chloride[7]	0.04	0.04	0.04	0.04
Total	100	100	100	100
Calculated analysis				
Standardized ileal digestible amino acids, %				
Lysine	1.33	1.33	1.33	1.33
Isoleucine:lysine	57	56	57	57
Leucine:lysine	117	116	117	116
Metthionine:lysine	37	37	37	37
Methionine and cysteine:lysine	58	58	58	58
Threonine:lysine	60	60	60	60
Tryptophan:lysine	19	19	19.1	19.1
Valine:lysine	67	67	67	67
Net energy, kcal/kg	2,429	2,385	2,452	2,401
Crude protein, %	21.3	21.2	20.5	20.4
Calcium, %	0.59	0.94	0.47	0.84
Phosphorus, %	0.51	0.80	0.40	0.71
Standardized total tract digestible phosphorus, %	0.26	0.53	0.30	0.58
Available phosphorus, %	0.19	0.49	0.23	0.54
Calcium:phosphorus	1.17	1.18	1.17	1.17

[1] In Exp. 1, diets were fed from 11.4- to 22.8-kg BW. Diets were blended to form the intermediate treatments: 0.30, 0.33, 0.38, 0.43, and 0.48% STTD P. In Exp. 2, diets were fed from 11.1- to 22.5- kg BW. Diets were blended to form the intermediate treatments: 0.33, 0.38, 0.43, 0.48, and 0.53% STTD P.

[2] STTD P = standardized total tract digestible phosphorus.

[3] Ronozyme HiPhos 2500 (DSM Nutritional Products, Parsippany, NJ) provided 1,000 FYT per kg of feed, releasing an assumed 0.15% avP and 0.132% STTD P.

[4] Provided per kg of premix: 8,818,490 IU vitamin A; 1,102,311 IU vitamin D; 35,273 IU vitamin E; 3,527.4 mg vitamin K; 30.9 mg vitamin B12; 39,683 mg niacin; 22,046 mg pantothenic acid; 6,614 mg riboflavin.

[5] Provided per kg of premix: 165 g Zn from Zn sulfate; 165 g Fe from iron sulfate; 40 g Mn from manganese oxide; 17 g Cu from copper sulfate; 0.3 g I from calcium iodate; 0.3 g Se from sodium selenite.

[6] Provided per kg of premix: 5,346,210 IU vitamin A; 1,338,206 IU vitamin D; 100,211 IU vitamin E; 1,671.1 mg vitamin K; 21.4 mg vitamin B12; 29,061 mg niacin; 15,366 mg pantothenic acid; 4,008 mg riboflavin, 73.5 g Zn from Zn sulfate; 66.8 g Fe from iron sulfate; 26.7 g Mn from manganese oxide; 10 g Cu from copper sulfate; 0.5 g I from calcium iodate; 0.2 g Se from sodium selenite.

[7] Supplemental copper provided in the form of tri-basic copper chloride (TBCC; Intellibond C; Micronutrients, Indianapolis, IN) at 150 ppm.

Chemical Analysis

Representative diet samples were obtained from all feeders of each treatment and delivered to the Kansas State University Swine Laboratory, Manhattan, KS, and stored at −20 °C until analysis. Samples of the diets were combined within dietary treatment, and a composite sample from each treatment was analyzed in duplicate (Ward Laboratories, Inc., Kearney, NE). Samples were analyzed for DM (method 935.29; AOAC International, 1990), CP (method 990.03; AOAC International, 1990), Ca (method 985.01; AOAC International, 1990), P (method 985.01; AOAC International, 1990), ash (method 942.05, AOAC International, 1990), and ether extract (method 969.10, AOAC International, 1990). In Exp. 2, a composite sample of the low (0.30% STTD P) and high (0.58% STTD P) diets was analyzed for phytase activity (method 300.24; AOAC International, 2009) in duplicate (New Jersey Feed Laboratory Inc., Trenton, NJ).

Statistical Analysis

Data from both experiments were analyzed as a randomized complete block design with block as a random effect and pen as the experimental unit. Polynomial contrasts were implemented to evaluate the functional form of the dose response to increasing dietary STTD P on ADG, ADFI, G:F, BW, grams of STTD P intake per day, and grams of STTD P intake per kilogram of gain. The coefficients for the unequally spaced linear and quadratic contrasts were derived using the IML procedure in SAS (Version 9.3, SAS Institute Inc., Cary, NC). Statistical models were fit using GLIMMIX procedure of SAS. Results were considered significant at $P \leq 0.05$ and marginally significant at $0.05 \leq P \leq 0.10$.

In addition, the effects of the STTD P levels on ADG and G:F were fit using procedures outlined by Gonçalves et al. (2016). Briefly, models were expanded to account for heterogeneous residual variances when needed. Competing statistical models included a linear (**LM**), quadratic polynomial (**QP**), broken-line linear (**BLL**), and broken-line quadratic (**BLQ**). Dose–response models were compared based on the Bayesian information criterion (**BIC**), where the smaller the value, the better (Milliken and Johnson, 2009). A decrease in BIC greater than 2 was considered a significant improvement in model fit. The 95% confidence interval of the estimated requirement to reach maximum performance was computed. Results reported correspond to inferences yielded by the best fitting models.

RESULTS

Chemical Analysis

The analyzed DM, CP, ether extract, ash, Ca, and P were consistent with formulated values (Tables 2 and 3). In both experiments, average values of analyzed P were approximately 7% lower than formulated values, which is still below the acceptable analytical variation (AAFCO, 2015). Analyzed P content increased with increasing STTD P treatments. Average values of analyzed Ca were approximately 7% and 15% higher than formulated values in Exp. 1 and Exp. 2, respectively. Chemical analysis of dietary Ca is typically more variable than P and the Ca analytical variability observed in this study is still within the acceptable variation based on AAFCO (2015). Moreover, they followed a stepwise increase as expected with the designed treatment structure. In Exp. 2, the analyzed phytase activity in the low (0.30% STTD P) and the high (0.58% STTD P) diets was 1,760 and 1,755 FYT/kg, respectively. Although the values of analyzed phytase activity were higher than formulated values, the resulting STTD P release according to the manufacturer would only represent an increase from 0.132% to 0.150%. In addition, the variability in the phytase analysis of complete diets is typically greater than the phytase analysis of pure products (Kim and Lei, 2005).

Experiment 1

Average daily gain, ADFI, and G:F increased (linear, $P < 0.05$; Table 4) with increasing STTD P. There was also a marginal response (quadratic, $P < 0.066$) for G:F, with the greatest improvement in G:F as STTD P increased from 0.26% to 0.33%. There was a significant linear effect ($P = 0.001$) of increasing STTD P on final BW. The greatest improvement in final BW, however, was observed at 0.43% STTD P. Grams of STTD P intake per day and grams of STTD P intake per kilogram of gain increased (linear, $P = 0.001$) with increasing levels of STTD P.

The responses for ADG and ADFI were not modeled due to their linear nature. Heterogeneous variance was used for feed efficiency models. Feed efficiency had similar fitting models

Table 2. Chemical analysis of diets (as-fed basis; Exp. 1)[1]

	STTD P[2], %						
Item, %	0.26	0.30	0.33	0.38	0.43	0.48	0.53
Dry matter	87.78	87.75	88.18	87.84	87.87	88.02	88.14
Crude protein	19.6	20.2	21.4	21.5	21.4	20.3	20.7
Ether extract	2.4	2.4	2.3	2.3	2.3	2.4	2.3
Ash	3.81	4.25	4.56	4.98	4.88	4.93	5.14
Calcium	0.65	0.74	0.73	0.85	0.90	0.82	0.88
Phosphorus	0.44	0.49	0.54	0.64	0.66	0.71	0.75

[1] A representative sample of each diet was collected from 6 feeders, homogenized, and then analyses were conducted on composite samples (Ward Laboratories, Inc., Kearney, NE). Low (0.26% STTD P) and high (0.53% STTD P) diets were blended at the farm by a robotic feeding system to create the 0.30%, 0.33%, 0.38%, 0.43%, and 0.48% STTD P dietary treatments.

[2] STTD P = standardized total tract digestible phosphorus.

Table 3. Chemical analysis of diets (as-fed basis; Exp. 2)[1]

	STTD P[2], %						
Item, %	0.30	0.33	0.38	0.43	0.48	0.53	0.58
Dry matter	88.42	88.53	89.20	88.83	88.90	88.51	88.60
Crude protein	18.23	19.68	20.40	19.60	20.60	19.20	19.23
Ether extract	2.30	2.03	2.05	2.23	2.33	2.15	2.13
Ash	3.62	3.96	4.52	4.57	4.55	4.76	5.11
Calcium	0.54	0.61	0.65	0.79	0.77	0.83	0.95
Phosphorus	0.33	0.42	0.46	0.52	0.58	0.60	0.66

[1] A representative sample of each diet was collected from 6 feeders, homogenized, and then analyses were conducted on composite samples (Ward Laboratories, Inc., Kearney, NE). Low (0.30% STTD P) and high (0.58% STTD P) diets were blended at the farm by a robotic feeding system to create the 0.33%, 0.38%, 0.43%, 0.48%, and 0.53% STTD P dietary treatments. A composite sample of the low (0.30% STTD P) and high (0.58% STTD P) diets was analyzed for phytase activity in duplicate (New Jersey Feed Laboratory Inc., Trenton, NJ). The analyzed phytase activity in the mixed diets was 1,760 and 1,755 FYT/kg, respectively.

[2] STTD P = standardized total tract digestible phosphorus.

Table 4. Least square means for growth performance of nursery pigs fed increasing standardized total tract digestible (STTD) P from 11- to 23-kg body weight (BW), Exp. 1[1]

		STTD P[2], %								Probability, P	
		0.26	0.30	0.33	0.38	0.43	0.48	0.53			
Item[3]	% of NRC[4]	80	90	100	115	130	145	160	SEM	Linear	Quadratic
Days 0 to 21											
ADG, g		513	510	533	532	566	563	573	11.6	<0.001	0.718
ADFI, g		782	764	776	780	818	824	828	19.4	0.004	0.603
G:F, g/kg		656	667	687	682	692	684	693	7.4	<0.001	0.066
STTD P, g/d		2.03	2.29	2.56	2.97	3.52	3.95	4.39	0.082	0.001	0.418
STTD P, g/kg gain		3.85	4.41	4.89	5.53	6.31	7.19	7.68	0.067	0.001	0.579
BW, kg											
d 0		11.4	11.4	11.4	11.4	11.4	11.4	11.4	0.29	0.935	0.933
d 21		22.2	22.2	22.6	22.7	23.3	23.3	23.5	0.92	0.001	0.759

[1] A total of 1,080 barrows and gilts (PIC; 337 × Camborough, initial pen average BW of 11.4 ± 0.29 kg) were used in a 21-d growth trial with 23 to 27 pigs per pen and 6 pens per treatment. Two groups of pigs were weaned at approximately 21 d of age, fed a common phase 1 and phase 2 diet for 21 or 24 d postweaning, then fed experimental diets. Low (0.26% STTD P) and high (0.53% STTD P) diets were blended at the farm by a robotic feeding system to create the 0.30%, 0.33%, 0.38%, 0.43%, and 0.48% STTD P dietary treatments.

[2] STTD P = Standardized total tract digestible phosphorus.

[3] ADG = average daily gain; ADFI = average daily feed intake; G:F = gain-to-feed ratio; BW = body weight.

[4] The NRC requirement estimate for nursery pigs from 11 to 25 kg, expressed as a percentage of the diet, is 0.33% STTD P. Therefore, treatment concentrations represented 80%, 90%, 100%, 115%, 130%, 145%, and 160% of the NRC (2012) requirement.

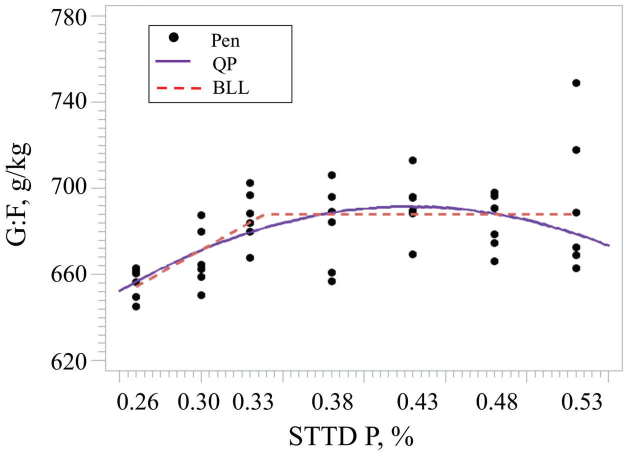

Figure 1. Fitted quadratic polynomial (QP) and broken-line linear (BLL) regression models on feed efficiency (G:F) as a function of increasing standardized total tract digestible (STTD) P in 11- to 23-kg pigs in Exp. 1. The QP model estimated the maximum mean G:F at 0.42% (95% CI: [0.36, >0.53]%), with 99% of maximum G:F achieved at 0.36%. The estimated regression equation was G:F, g/kg = 456.59 + 1107.49 × (STTD P) − 1307.16 × (STTD P)^2. The BLL breakpoint was estimated at 0.34% (95% CI: [0.30, 0.37]%).The estimated regression equation was G:F, g/kg = 696.63 − 427.26 × (0.3358 − STTD P) if STTD P < 0.34%, and G:F, g/kg = 696.63 if STTD P ≥ 0.34%.

for the BLL and QP (Figure 1). The BLL breakpoint for G:F was estimated at 0.34% (95% CI: [0.30, 0.37%]) STTD P and the regression equation was

$$\begin{aligned}\mathrm{G:F,\ g/kg} &= 696.63 - 427.26\\ &\quad\times(0.3358-\mathrm{STTD\ P})\\ &\quad\mathrm{if\ STTD\ P} < 0.34\ \%,\end{aligned}$$

$$\mathrm{G:F,\ g/kg} = 696.63\ \mathrm{if\ STTD\ P} \geq 0.34\ \%\ .$$

For the QP model, the maximum G:F was estimated at 0.42% (95% CI: [0.36, > 0.53%]) STTD P, with 99% of maximum performance being achieved with 0.36% STTD P. The regression equation for the QP model was

$$\begin{aligned}\mathrm{G:F,\ g/kg} &= 456.59 + 1107.49\\ &\quad\times(\mathrm{STTD\ P}) - 1307.16\\ &\quad\times(\mathrm{STTD\ P})^2.\end{aligned}$$

Experiment 2

Increasing STTD P improved (quadratic, $P < 0.05$) ADG and G:F (Table 5). The greatest improvement was observed as the STTD P increased from 0.30% to 0.43% for ADG, and from 0.30% to 0.38% for G:F, with no improvements thereafter. Average daily feed intake increased (linear, $P = 0.060$) with increasing the STTD P, with the highest feed intake observed at 0.48% STTD P. There was a significant linear response ($P = 0.028$) in final BW. The heaviest final weight, however, was observed at 0.43% STTD P. Also, grams of STTD P intake per day and grams of STTD P intake per kilogram of gain increased (linear, $P < 0.001$) with increasing levels of STTD P.

The response for ADFI was not modeled due to its linear nature. Homogeneous variance was used for ADG models and heterogeneous variance was used for feed efficiency models. The best fitting model was the BLL for ADG and G:F. The BLL breakpoint for ADG was estimated at 0.40% (95% CI: [0.33, 0.47]%) STTD P (Figure 2). Based on the best fitting model, the estimated regression equation was

$$\begin{aligned}\mathrm{ADG,\ g} &= 543.97 - 289.79\\ &\quad\times(0.3993-\mathrm{STTD\ P})\\ &\quad\mathrm{if\ STTD\ P} < 0.40\ \%,\end{aligned}$$

$$\mathrm{ADG,\ g} = 543.97\ \mathrm{if\ STTD\ P} \geq 0.40\ \%$$

For G:F, the breakpoint was estimated at 0.37% (95% CI: [0.29,0.45]%) STTD P, and the regression equation for the BLL model (Figure 3) was

Table 5. Least square means for growth performance of nursery pigs fed increasing standardized total tract digestible (STTD) P from 11- to 23-kg body weight (BW), Exp. 2[1]

	STTD P[2], %[3]									
	0.30	0.33	0.38	0.43	0.48	0.53	0.58		Probability, *P*	
Item[4] % of NRC[5]	90	100	115	130	145	160	175	SEM	Linear	Quadratic
Days 0 to 21										
ADG, g	515	523	539	549	547	542	545	8.6	<0.001	0.009
ADFI, g	747	749	753	768	773	770	762	15.4	0.060	0.198
G:F, g/kg	691	700	716	715	708	706	716	5.6	0.002	0.027
STTD P, g/d	2.24	2.47	2.86	3.30	3.71	4.07	4.42	0.072	<0.001	0.321
STTD P, g/kg gain	4.34	4.72	5.31	6.01	6.79	7.51	8.10	0.049	<0.001	0.223
BW, kg										
d 0	11.1	11.1	11.1	11.1	11.1	11.1	11.1	0.24	0.978	0.990
d 21	22.0	22.2	22.5	22.7	22.6	22.6	22.6	0.39	0.028	0.125

[1] A total of 2,140 pigs (PIC 337 × Camborough, initial pen average BW of 11.1 ± 0.24 kg) were used in a 21-d growth trial with 24 to 27 pigs per pen and 12 pens per treatment. Pigs were weaned at approximately 19 d of age, fed a common phase 1 and phase 2 diets for 25 d postweaning, then fed experimental diets. Low (0.30% STTD P) and high (0.58% STTD P) diets were blended at the farm by a robotic feeding system to create the 0.33%, 0.38%, 0.43%, 0.48%, and 0.53% STTD P dietary treatments.
[2] STTD P = Standardized total tract digestible phosphorus.
[3] Phytase (Ronozyme HiPhos, DSM Nutritional Products, Parsippany, NJ) was included at 1000 FYT/kg releasing an assumed 0.15% avP and 0.132% STTD P.
[4] ADG = average daily gain; ADFI = average daily feed intake; G:F = gain-to-feed ratio; BW = body weight.
[5] The NRC requirement estimate for nursery pigs from 11 to 25 kg, expressed as a percentage of the diet, is 0.33% STTD P. Therefore, treatment concentrations represented 90%, 100%, 115%, 130%, 145%, 160%, and 175% of the NRC (2012) requirement.

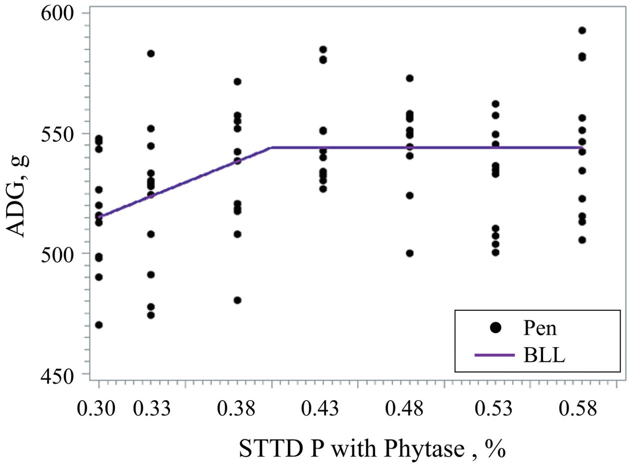

Figure 2. Fitted broken-line linear (BLL) regression model on average daily gain (ADG) as a function of increasing standardized total tract digestible (STTD) P with 1,000 added phytase units in 11- to 23-kg pigs in Exp 2. The BLL breakpoint was estimated at 0.40% (95% CI: [0.33, 0.47]%). Based on the best fitting model, the estimated regression equation was ADG, g = 543.97 – 289.79 × (0.3993 – STTD P) if STTD P < 0.40%, and ADG, g = 543.97 if STTD P ≥ 0.40%.

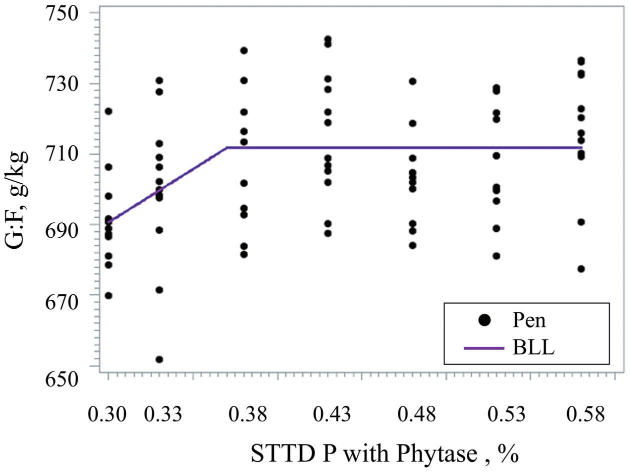

Figure 3. Fitted broken-line linear (BLL) regression model on feed efficiency (G:F) as a function of increasing standardized total tract digestible (STTD) P with 1,000 added phytase units in 11- to 23-kg pigs in Exp. 2. The BLL breakpoint was estimated at 0.37% (95% CI: [0.29, 0.45]%). Based on the best fitting model, the estimated regression equation was G:F, g/kg = 711.76 – 301.08 × (0.37 – STTD P) if STTD P < 0.37%, and G:F, g/kg = 711.76 if STTD P ≥ 0.37%.

$$\begin{aligned} \mathrm{G:F,\ g/kg} &= 711.76 - 301.08 \\ &\quad \times (0.37 - \mathrm{STTD\ P}) \\ &\quad \mathrm{if\ STTD\ P} < 0.37\ \%, \end{aligned}$$

$$\mathrm{G:F,\ g/kg} \ = \ 711.76 \mathrm{\ if\ STTD\ P} \geq 0.37\ \%$$

The ADG was also modeled as a function of STTD P intake in grams per day. The BLL and BLQ models has similar fit (Figure 4). The BLL breakpoint was estimated at 2.92 g/d (95% CI: [2.56, 3.27g/d]) STTD P and the regression equation was

$$\begin{aligned} \mathrm{ADG,\ g} &= 545.11 - 51.3991 \\ &\quad \times (2.917 - \mathrm{STTD\ P\ in\ g/d}) \\ &\quad \mathrm{if\ STTD\ P\ intake} < 2.92\ \mathrm{g/d}, \end{aligned}$$

$$\mathrm{ADG,\ g} = 545.11 \mathrm{\ if\ STTD\ P\ intake} \geq 2.92\ \mathrm{g/d}.$$

The BLQ breakpoint was estimated at 3.02 g/d (95% CI: [3.00, 3.03g/d]) STTD P. The regression equation for the BLQ model was

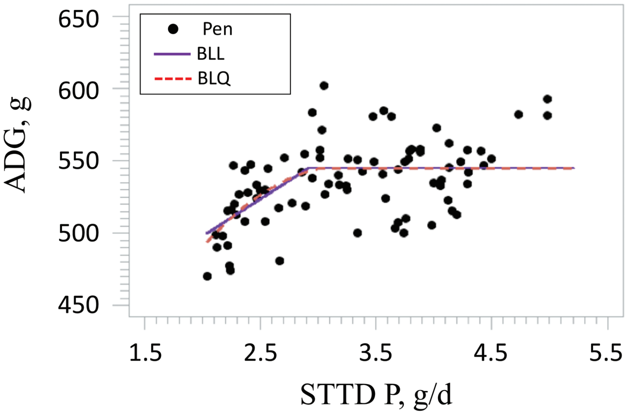

Figure 4. Fitted broken-line linear (BLL) and broken-line quadratic (BLQ) regression models on average daily gain (ADG) as a function of increasing standardized total tract digestible (STTD) P intake in grams per day in 11- to 23-kg pigs fed diets with 1,000 added phytase units in Exp 2. The BLL breakpoint was estimated at 2.92 g/d (95% CI: [2.56, 3.27g/d]) STTD P. Based on the BLL model, the estimated regression equation was ADG, g = 545.11 – 51.3991 × (2.917 – STTD P in g/d) if STTD P intake < 2.92 g/d, and ADG, g = 545.11 if STTD P intake ≥ 2.92 g/d. The BLQ breakpoint was estimated at 3.02 g/d (95% CI: [3.00, 3.03g/d]) STTD P. Based on the BLQ model, the estimated regression equation was ADG, g = 544.96 – 17.2077 × (3.019 – STTD P in g/d) – 35.7972 × (3.019 – STTD P in g/d)^2 if STTD P intake < 3.02 g/d, and ADG, g = 544.96 if STTD P intake ≥ 3.02 g/d.

$$\begin{aligned}\text{ADG, g} \;=\; & 544.96 - 17.2077 \times (3.019 - \text{STTD P in g/d}) - 35.7972 \\ & \times (3.019 - \text{STTD P in g/d})^2 \\ & \text{if STTD P intake} < 3.02\ \text{g/d},\end{aligned}$$

$$\text{ADG, g} = 544.96 \text{ if STTD P intake} \geq 3.02\ \text{g/d}.$$

Discussion

In 2012, the NRC started to express the P requirement estimate by pigs on a STTD basis. The STTD P measures the digestible P utilization while accounting for the basal endogenous losses. The STTD P can be utilized in diet formulation as it is additive in mixed diets fed to pigs (NRC, 2012). The current study was designed to provide more information of the STTD P requirement of nursery pigs.

Limited research has evaluated the STTD P requirement of nursery pigs. Recent research conducted by Wu et al., (2018) determined the P requirement for growth performance of weaned pigs from 6- to 13-kg pigs when offered diets formulated to contain graded levels of STTD P that ranged from 80% to 140% of NRC on a diet concentration basis. Similar to our findings, higher STTD P estimates than the NRC (2012) requirement estimates were observed. For ADG, the BLL model estimated the requirement as 91% of the NRC (2012), whereas the more sensitive QP model resulted in a higher requirement estimate of 117% of NRC (2012). Depending on the statistical model, the estimated STTD P requirement for maximum feed efficiency ranged from 102% to greater than 140% of NRC (2012). The NRC (2012) estimated the STTD P requirement for 11- to 23-kg pigs at 0.33% of the diet. It is important to acknowledge that the NRC estimates the STTD P requirement of nursery pigs weighing less than 20 kg BW using a simple mathematical regression approach. Therefore, the requirement for STTD P as a percentage of the diet is related to the animal's BW as follows:

$$\text{STTD P requirements } (\% \text{ of diet}) = 0.6418 - 0.1083 \times \ln(\text{BW}).$$

Only 2 empirical published studies conducted by Coalson et al., (1972) and Mahan et al., (1980) with less than 20 kg BW pigs were deemed appropriate to allow the determination of a requirement estimate (NRC, 2012). They date over 30 yr from the NRC publication date, emphasizing the lack of research within this BW range pigs and the need for more empirical data to validate the requirement estimate. In Exp. 1, we observed that feeding 0.34% to at least 0.54% STTD P improved G:F and ADG, respectively, with the requirement for maximum ADG being greater than that for maximum G:F. However, diminishing returns were observed in growth rate at STTD P greater than 0.43%. Moreover, at this point of diminishing returns in response to increased STTD P, the grams of STTD P intake per day and grams of STTD P intake per kilogram of gain were 3.52 g/d and 6.31 g/kg of gain. These values are greater than NRC (2012) requirement estimate of 2.99 g/d and the 5.11 g/kg of gain calculated from the 585 g/d of BW gain suggested by NRC (2012) publication. According to Van Milgen and Noblet (1999), approximately 53% to 60% of the energy intake above maintenance of pigs weighing 20 kg goes to protein deposition. Thus, a greater portion of the growth rate of pigs in the current study is likely protein growth, with greater P intake needed to support the protein gain as the muscle tissue contains higher amounts of P compared with fat tissue (Nielsen, 1973). Moreover, the demand for P increases as the ratio of lean tissue growth increases (Jongbloed, 1987). Therefore, the higher requirement for P intake in grams per kilogram of gain observed in the current study may be a consequence of genetic improvement in growth performance and carcass lean meat content of pigs (Partanen et al., 2010).

A considerable amount of phosphorus titration studies of growing-finishing pigs has been reported in the literature (Ekpe et al., 2002; Partanen et al., 2010; Zhai and Adeola, 2013; Adeola et al., 2015). Observations from our study corroborate these studies, which suggest that the P requirements for pig growth performance are greater than the NRC (2012) estimates. As an example, the NRC (2012) STTD P estimate for 25- to 50-kg pigs is 0.31%. Ekpe et al., (2002) estimated the STTD P requirement for 23.5- to 60-kg pigs between 0.35% and 0.38% to support maximum growth rate and feed efficiency. Breakpoints from nonlinear broken-line regression models were determined for 19- to 40-kg pigs (Adeola et al., 2015). The STTD P requirement was estimated at 0.39% and 0.41% to maximize ADG and G:F, respectively. These studies, however, evaluated the digestible P requirement of heavier BW pigs compared with the current study.

Concentration of P in the body is closely related to the concentration of Ca, and an excess or deficiency of one mineral may affect the utilization of the other (Crenshaw et al., 2001). Thus, it is important to consider an appropriate ratio between Ca and P for diet formulations. Two different approaches are commonly used in studies that are designed to determine the requirement of Ca or P. They can be structured to contain graded values of the mineral of interest while maintaining the other constant, or alternatively, they can be structured to contain a constant Ca:P ratio. In a study designed to determine the P requirement with a constant level of Ca, a high Ca or wide Ca:P ratio could be detrimental to performance in the low P diets, whereas Ca could be a limiting nutrient in high P diets. In low P diets, excess Ca could lead to the formation of Ca-P complexes in the gastrointestinal tract, reducing P digestibility and absorption (Stein et al., 2011; González-Vega and Stein, 2014). In high P diets, Lagos et al. (2019) reported that growth rate was reduced in diets containing low Ca compared with diets containing Ca above the requirement. The authors raised the possibility that binding of Ca may also occur by excess P. According to results from González-Vega et al. (2016), increasing the concentration of STTD Ca in diets containing a constant concentration of STTD P is detrimental to pig performance. Conversely, the authors also observed that lower STTD Ca concentration in the diet fed during a short period of time was not detrimental to pig growth performance. The current study utilized the approach of maintaining a constant analyzed Ca:P ratio of 1.17:1. Thus, diets with low P concentration were also formulated with lower Ca concentration, which could have potentially favored the low P treatments.

Moreover, Ca release by phytase was not accounted in the diet formulation in Exp. 2. We acknowledge that we formulated the diets based on a constant analyzed Ca:P ratio. Coefficients for STTD of P in feed ingredients were obtained from NRC (2012), and values for STTD of Ca were obtained from Stein et al. (2016). The STTD Ca concentrations in the diets in both experiments were recalculated, including the 0.096% STTD Ca release by phytase as recommended by the manufacturer (DSM Nutritional Products, Inc., Parsippany, NJ). The STTD Ca:STTD P ratio ranged between 1.53:1 and 1.20:1, with wider ratios observed at lower P levels. Therefore, the reduced growth performance in the low P treatments could be further decreased than what would be observed merely due to P inadequacy. Lagos et al. (2019) observed that when the STTD P is provided at the recommended level by NRC (2012) of 0.33%, the ratio to maximize ADG of 11 to 22 kg pigs was at 1.39:1 STTD Ca:STTD P. Detrimental effects with STTD P in excess of NRC (2012) were only observed at STTD Ca levels greater than 0.60%, which was the case of the highest dietary treatments in the current study. The authors also described that the ratio to maximize growth rate when STTD P was provided at 0.42% was 1.28:1 STTD Ca:STTD P. In the current study, the STTD P to optimize growth rate was determined at approximately 0.43%. At this STTD P concentration, the calculated STTD Ca:STTD P ratios were 1.31:1 and 1.28:1 in Exp. 1 and Exp. 2, respectively, corroborating with the results described by Lagos et al. (2019).

In addition, it is worthwhile to consider that approximately 60% to 80% of P in feedstuffs of plant origin is stored in phytic acid, typically in the form of phytate (Eeckout and De Paepe, 1994). Pigs lack sufficient endogenous phytase to effectively cleave the phosphates from the phytate. Thus, phytate is known as an antinutritional factor in swine diets (Swick and Ivey, 1992) as it reduces P digestibility. A practical and economical solution to this problem consists of adding an exogenous phytase source to swine diets, which has the ability to dephosphorylate the phytate in a step-wise manner and liberate P. As a consequence, P availability to the pig is increased while a need for the addition of expensive inorganic sources of P in the diet is decreased (Selle and Ravindran, 2008).

According to Almeida and Stein (2010), swine diets formulated with the addition of phytase and less inorganic P result in a reduction in P excretion in the environment without negatively effecting growth performance. Wu et al. (2018) also titrated the STTD P in diets for early nursery pigs containing 2,000 FYT of phytase. When phytase was added in the diets, the estimated maximum ADG occurred at 138% of the NRC (2012) using the QP model, whereas the maximum G:F was estimated at 147% and 116% of the NRC (2012) using the QP and BLL models, respectively. These results are in accordance with the observations in Exp. 2, in which a greater STTD P requirement compared with the NRC (2012) was estimated for late nursery pigs fed diets containing 1,000 FYT phytase. Moreover, compared with Exp. 1, in Exp. 2 more replicates per treatment were utilized and a breakpoint for maximum ADG was estimated through a BLL model at 0.40% STTD P. The estimated breakpoint is fairly consistent with the point of diminishing returns in growth rate in Exp. 1 at 0.43%, suggesting that the recommended manufacturer releasing ability of 1,000 FYT phytase of 0.132% STTD P used in the present study was accurate. In addition, the breakpoints for STTD P intake in grams per day for pigs fed diets containing phytase were 2.92 and 3.02 g/d. These values are very similar to the NRC (2012) STTD P requirement estimate of 2.99 g/d, suggesting that the NRC requirement estimates of STTD P by nursery pigs are accurate on a grams per day basis. Similar to Exp. 1, in Exp. 2 the STTD P intake in grams per kilogram of gain was greater than the 5.11 g/kg gain calculated from the 585 g/d of BW gain suggested by NRC (2012) publication.

These data provide empirical evidence that the NRC (2012) accurately determines the STTD P requirement by nursery pigs on a grams per day basis. However, as a percentage of the diet, NRC (2012) underestimates the STTD P requirement for G:F and ADG of 11- to 23-kg nursery pigs. Our results suggest that, depending on the response criteria and statistical model, the STTD P level as a percentage of the diet to optimize growth performance of 11- to 23-kg pigs fed diets without or with 1,000 FYT added phytase ranged from 0.34% to 0.42% STTD P. Practical implications of this are that many swine nutritionists use the dietary percentages as a baseline for setting requirement estimates which can lead to under-estimating STTD P concentrations. However, if accurate feed intake measurements are available, the NRC estimated requirements on a grams per day basis can be translated into more accurate baseline dietary percentage recommendations. Also, this supports that the underlying assumptions used in developing NRC requirement estimates are accurate.

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