Animal Feed Science and Technology 280 (2021) 115084

Contents lists available at ScienceDirect

Animal Feed Science and Technology

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

Comparative digestibility and retention of calcium and phosphorus in normal- and high-phytate diets fed to gestating sows and growing pigs

S.A. Lee [a], M.R. Bedford [b], H.H. Stein [a,*]

[a] Department of Animal Sciences, University of Illinois, Urbana 61801, IL, United States
[b] AB Vista, Marlborough SN8 4AN, United Kingdom

ARTICLE INFO

Keywords:
Calcium
Digestibility
Endogenous loss
Phosphorus
Retention
Sow

ABSTRACT

The objective of this research was to test the hypothesis that calculated values for standardized total tract digestibility (STTD) and retention of Ca and P are not different between gestating sows and growing pigs. A total of 32 gestating sows (day of gestation = 40) and 32 castrates (body weight = 19.8 kg) were placed in metabolism crates. Two diets were formulated to contain 9.8 or 29.4 g/kg phytate. Diets were formulated based on corn, soybean meal, Ca carbonate, and dicalcium phosphate and the high-phytate diet also contained 400 g/kg full-fat rice bran. A Ca-free diet and a P-free diet were used to determine basal endogenous losses of Ca and P. Feces and urine were collected for 4 days after 4 days of adaptation. Results indicated that basal endogenous losses of Ca and P from gestating sows were greater ($P < 0.05$) than from growing pigs. The digestibility of dry matter was not affected by the physiological state of the animals, but was greater ($P < 0.001$) in the normal-phytate diet than in the high-phytate diet. Phytate level did not affect the STTD of Ca or Ca retention by gestating sows, but the STTD of Ca and Ca retention were greater if growing pigs were fed the normal-phytate diet than if they were fed the high-phytate diet (physiological state × phytate level interaction; $P < 0.001$). The STTD of P was greater for the normal-phytate diet than for the high-phytate diet, but the difference was greater for growing pigs than for gestating sows (physiological state × phytate level interaction; $P = 0.002$). Phosphorus retention by growing pigs fed the normal-phytate diet was greater than if they were fed the high-phytate diet, but P retention by gestating sows was not affected by phytate level (physiological state × phytate level interaction; $P < 0.001$). Regardless of phytate level, gestating sows had reduced ($P < 0.001$) STTD of Ca and P and reduced retention of Ca and P compared with growing pigs. In conclusion, gestating sows have reduced digestibility and retention of Ca and P, but increased basal endogenous losses of Ca and P, compared with growing pigs. Response to dietary phytate is different for STTD and retention of Ca and P between gestating sows and growing pigs. It may, therefore, not always be accurate to formulate diets for gestating sows using digestibility values for Ca and P that were obtained in growing pigs.

Abbreviations: aNDF, neutral detergent fiber that was assayed with a heat stable amylase and expressed inclusive of residual ash; ADF, acid detergent fiber that was expressed inclusive of residual ash; ATTD, apparent total tract digestibility; BW, body weight; STTD, standardized total tract digestibility.

* Corresponding author.
E-mail address: hstein@illinois.edu (H.H. Stein).

https://doi.org/10.1016/j.anifeedsci.2021.115084
Received 6 February 2021; Received in revised form 26 August 2021; Accepted 27 August 2021
Available online 3 September 2021
0377-8401/© 2021 Elsevier B.V. All rights reserved.

1. Introduction

Digestibility of energy and some nutrients may be affected by age, body weight (**BW**), and physiological state of the animal and gestating sows usually have greater digestibility of energy than growing pigs (Le Goff and Noblet, 2001; Casas and Stein, 2017). Coefficients for digestibility of Ca and P are most correctly determined as standardized total tract digestibility (**STTD**; NRC, 2012; Stein et al., 2016). Data for the STTD of P in most feed ingredients have been published (NRC, 2012), and the digestibility of Ca has also been determined in many feed ingredients (Stein et al., 2016; Zhang et al., 2016). Most values for STTD of Ca and P in feed ingredients have been determined in growing pigs (González-Vega et al., 2015a; Zhang and Adeola, 2017; Lee et al., 2019b). It is, however, not known if the STTD of Ca and P is different between gestating sows and growing pigs, but in practical diet formulation, values for STTD of Ca and P obtained in growing pigs are also applied to sows. Therefore, the objective of this experiment was to test the hypothesis that no differences exist between gestating sows and growing pigs for apparent total tract digestibility (**ATTD**), STTD, and retention of Ca and P when growing pigs and sows are fed the same diets.

2. Materials and methods

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for this experiment. Camborough sows (PIC, Hendersonville, TN, USA) were used and growing pigs were the offspring of Line 359 boars that were mated to Camborough females (Pig Improvement Company, Hendersonville, TN, USA).

2.1. Diets and feeding

Corn, soybean meal, rice bran, Ca carbonate, and dicalcium phosphate were used to prepare diets (Table 1). Four diets were used in the experiment (Table 2). Two diets were formulated to contain a normal or high amount of phytate with the extra phytate in the high-phytate diet being supplied by inclusion of 400 g/kg full-fat rice bran in the diet. A Ca-free diet and a P-free diet were also formulated to determine the basal endogenous losses of Ca and P, respectively. All vitamins and minerals except Ca and P were included in all diets to meet current requirements (NRC, 2012). Concentrations of Ca and P in the normal- and high-phytate diets met the requirement estimates for growing pigs whereas the Ca and P in the 2 diets exceeded requirement estimates for sows by about 1.3 times (NRC, 2012). Daily feed allotments were provided in 2 equal meals that were provided at 0700 and 1600 h. The daily feed allowance for gestating sows was 1.5 times the maintenance energy requirement calculated based on the BW of sows (i.e., 100 kcal metabolizable energy/kg $BW^{0.75}$; NRC, 2012), and growing pigs were provided feed in an amount that was calculated as 3 times the maintenance energy requirement (i.e., 197 kcal metabolizable energy/kg $BW^{0.60}$; NRC, 2012). Orts were collected after feeding to calculate total feed intake. Water was available at all times.

2.2. Animals and housing

A total of 32 gestating sows (BW = 248.8 ± 20.7 kg; parity = 2.48 ± 1.26; day of gestation = 40 ± 5 d) were allotted to the 4 diets using a randomized complete block design with 4 blocks of 8 sows and 2 sows per diet in each block for a total of 8 replicate sows per diet. Breeding group was the blocking factor. Before the start of the experiment, sows were fed a standard gestation diet that contained 7.2 g/kg Ca and 5.3 g/kg P, as-fed. Sows were housed individually in metabolism crates that were equipped with fully slatted floors, a feeder, and a cup waterer. A screen floor and a urine pan were installed below the slatted floor.

Thirty-two growing barrows (initial BW = 19.8 ± 1.0 kg) were also housed individually in metabolism crates and allotted to 4 diets

Table 1
Analyzed nutrient composition of feed ingredients used in diets for gestating sows and growing pigs, as-is basis.

Item, g/kg	Corn	Soybean meal	Rice bran	Calcium carbonate	Dicalcium phosphate
Dry matter	865.7	907.2	924.7	1000.0	939.4
Gross energy, MJ/kg	16.1	17.7	19.7	–	–
Crude protein	70.4	505.2	138.4	–	–
Ash	8.7	58.9	87.8	906	841
Acid-hydrolyzed ether extract	29.0	9.6	181.7	–	–
aNDF[a]	87.4	49.4	165.0	–	–
ADF[a]	24.6	23.3	67.6	–	–
Ca	0.1	3.4	0.5	390	220
Total P	2.4	7.2	19.8	0.1	184
Phytate[b]	7.4	17.0	65.2	–	–
Phytate-bound P	2.1	4.8	18.4	–	–
Phytate-bound P:total P	0.88	0.67	0.93	–	–
Non-phytate P[c]	0.3	2.4	1.4	–	–

[a] aNDF = neutral detergent fiber that was assayed with a heat stable amylase and expressed inclusive of residual ash; ADF = acid detergent fiber that was expressed inclusive of residual ash.
[b] Phytate was calculated by dividing the analyzed phytate-bound P by 0.282 (Tran and Sauvant, 2004).
[c] Non-phytate P was calculated as the difference between total P and phytate-bound P.

and 2 blocks of 16 pigs using a randomized complete block design. Weaning group was the blocking factor. There were 4 replicate pigs per diet in each block and, therefore, there were a total of 8 replicate pigs per diet.

2.3. Method of collection

The experimental period lasted approximately 10 days with the initial 4 days being the adaptation period to the diets followed by 4 days of total collection of feces and urine using the marker to marker procedure (Adeola, 2001). Feces and urine were collected separately. Fecal collection was initiated when the first marker (i.e., indigo carmine) that was supplemented in the morning meal on day 5 appeared in the feces and ceased when the second marker (i.e., ferric oxide), which was added to the morning meal on day 9, appeared (Adeola, 2001). Therefore, fecal and urine materials were collected from the feed provided on days 5, 6, 7, and 8. Feces were stored at -20 °C as soon as collected

Urine collections were initiated on day 5 at 0900 h and ceased on day 9 at 0900 h. Urine was collected in buckets placed under the metabolism crates with 50 mL of 3 *N* HCl. Buckets were emptied daily, the weight of the collected urine was recorded, and one tenth of the collected urine was stored at -20 °C until subsampling.

2.4. Chemical analyses

At the conclusion of the experiment, fecal samples were pooled within animal, dried at 65 °C in a forced air oven, and ground using a Wiley mill (Model 4; Thomas Scientific, Swedesboro, NJ, USA) through a 1-mm screen. Urine samples were thawed and mixed within animal and subsamples were collected for analysis.

Calcium and P in ingredients, diets, feces, and urine samples were analyzed by inductively coupled plasma spectroscopy (AOAC, 2007; method 985.01A, B, and C) after wet ash sample preparation [AOAC, 2007; method 975.03 B(b)]. Feed ingredients and diets were also analyzed for phytate-bound P (Megazyme method; ESC, Ystrad Mynach, UK). All ingredient and diet samples were analyzed for dry matter (AOAC, 2007; method 930.15), ash (AOAC, 2007; method 942.05), and gross energy using an isoperibol bomb calorimeter (Model 6400; Parr Instruments, Moline, IL, USA). Fecal samples were also analyzed for dry matter. Crude protein in feed ingredients and diets was calculated as N × 6.25 and N was analyzed by combustion (AOAC, 2007; method 990.03) using an Elementar Rapid N-cube Protein/Nitrogen Apparatus (Elementar Americas Inc., Mt Laurel, NJ, USA). Acid-hydrolyzed ether extract in ingredient and diet samples were analyzed by acid hydrolysis using 3 *N* HCl (Ankom HCl Hydrolysis System, Ankom Technology, Macedon, NY, USA) followed by fat extraction (Ankom XT-15 Extractor, Ankom Technology, Macedon, NY, USA). Ingredients and diets were also

Table 2
Ingredient composition of experimental diets fed to gestating sows and growing pigs, as-fed basis.

	Phytate level		Ca-free	P-free
Ingredient, g/kg	Normal	High		
Ground corn	726.9	382.9	767.5	–
Soybean meal, 480 g/kg crude protein	240.0	190.0	–	–
Rice bran, full-fat	–	400.0	–	–
Cornstarch	0.1	0.1	–	462.4
Potato protein concentrate	–	–	170.0	–
Gelatin	–	–	–	200.0
Sucrose	–	–	–	200.0
Soybean oil	–	–	40.0	40.0
Cellulose	–	–	–	50.0
$_{L}$-lysine·HCl, 780 g/kg lysine	4.0	3.7	–	4.5
$_{DL}$-methionine	1.0	1.0	–	1.4
$_{L}$-threonine	1.0	1.0	–	2.9
$_{L}$-tryptophan	–	–	–	1.7
$_{L}$-histidine	–	–	–	2.3
$_{L}$-isoleucine	–	–	–	3.2
$_{L}$-leucine	–	–	–	5.8
$_{L}$-valine	–	–	–	2.8
Calcium carbonate	8.0	13.5	–	12.0
Dicalcium phosphate	13.0	1.8	–	–
Monosodium phosphate	–	–	11.5	–
Potassium carbonate	–	–	4.0	4.0
Magnesium oxide	–	–	1.0	1.0
Salt	4.0	4.0	4.0	4.0
Vitamin-mineral premix[a]	2.0	2.0	2.0	2.0

[a] The vitamin-mineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2208 IU; vitamin E as $_{DL}$-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 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, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate; Fe, 126 mg as iron sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganous sulfate; Se, 0.25 mg as sodium selenite and selenium yeast; and Zn, 124.9 mg as zinc sulfate.

analyzed for acid detergent fiber and neutral detergent fiber using Ankom Technology method 12 and 13, respectively (Ankom 2000 Fiber Analyzer, Ankom Technology, Macedon, NY, USA). Neutral detergent fiber was assayed with a heat stable amylase and expressed inclusive of residual ash and acid detergent fiber was expressed inclusive of residual ash. All chemical analyses were performed in duplicates with the exception that Ca in diets were analyzed in quadruplicates.

2.5. Calculations

The ATTD of Ca and P in experimental diets was calculated as previously outlined (Almeida and Stein, 2010):

$$\text{ATTD of Ca or P} = \frac{\text{intake of Ca or P} - \text{output of Ca or P}}{\text{intake of Ca or P}}$$

where Ca and P intake and output in feces are expressed as g per day.

Basal endogenous losses of Ca and P that were estimated as the fecal flow of Ca and P from animals fed the Ca- and P-free diets were expressed as g/kg of dry matter intake and used to calculate the STTD of Ca and P (Almeida and Stein, 2010):

$$\text{STTD of Ca or P} = \text{ATTD of Ca or P} + \frac{\text{basal endogenous loss of Ca or P}}{\text{intake of Ca or P}}.$$

Basal endogenous losses of Ca and P expressed as g per day from pigs fed the normal- and high-phytate diets were calculated by multiplying the respective values for basal endogenous losses of Ca and P by the daily dry matter intake of pigs.

Retained Ca and P expressed as g per day was calculated using the following equation (Petersen and Stein, 2006):

$$\text{Retained Ca or P} = \text{intake of Ca or P} - (\text{fecal} + \text{urinary output of Ca or P})$$

where Ca and P intake and output in feces and urine are expressed as g per day.

Retention of Ca and P was calculated using the following equation (Petersen and Stein, 2006):

$$\text{Retention of Ca or P} = \frac{\text{retained Ca or P}}{\text{intake of Ca or P}}$$

where intake of Ca and P and retained Ca and P are expressed as g per day.

2.6. Statistical analysis

Normality and homogeneity of residuals were verified using the UNIVARIATE and MIXED procedures of SAS (SAS, 2018). Outliers were identified as values that were plotted outside 'inner fences' within treatment (Tukey, 1977). The animal was the experimental unit for all analyses. Data were analyzed using PROC MIXED of SAS that provided residual maximum likelihood estimates of variance and covariance components in the model. The statistical model included physiological state, phytate level in the diet, and the interactions between physiological state and phytate level as fixed effects, and block and replicate within block as random effects. To explain interactions, mean separation was conducted by the PDIFF option with the Tukey's adjustment. The basal endogenous losses of Ca and P by gestating sows and growing pigs that were fed Ca-free or P-free diets were also compared using a Student's unpaired *t*-test.

Table 3
Analyzed nutrient composition of experimental diets fed to gestating sows and growing pigs, as-fed basis.

	Phytate level		Ca-free	P-free
Item, g/kg	Normal	High		
Dry matter	889.9	916.8	892.7	941.7
Gross energy, MJ/kg	15.9	17.6	17.6	17.1
Metabolizable energy[a], MJ/kg	13.7	13.2	14.9	16.2
Crude protein	172.5	184.0	189.4	217.5
Ash	45.8	66.1	26.7	25.4
Acid-hydrolyzed ether extract	27.0	89.4	71.6	38.7
aNDF[b]	59.8	109.5	62.2	46.7
ADF[b]	14.3	42.8	17.3	39.5
Ca	7.3	7.2	0.2	5.0
Total P	6.1	10.6	5.0	0.1
Phytate[c]	9.6	28.4	–	–
Phytate-bound P	2.7	8.0	–	–
Phytate-bound P:total P	0.44	0.75	–	–
Non-phytate P[d]	3.4	2.6	–	–

[a] Values for metabolizable energy were calculated based on the metabolizable energy in feed ingredients reported in NRC (2012).

[b] aNDF = neutral detergent fiber that was assayed with a heat stable amylase and expressed inclusive of residual ash; ADF = acid detergent fiber that was expressed inclusive of residual ash.

[c] Phytate was calculated by dividing the analyzed phytate-bound P by 0.282 (Tran and Sauvant, 2004).

[d] Non-phytate P was calculated as the difference between total P and phytate-bound P.

Statistical significance was considered at $P < 0.05$.

3. Results

Gestating sows and growing pigs remained healthy during the experiment and very little feed refusals were observed. Analyzed concentrations of Ca, total P, and phytate in all experimental diets were in agreement with formulated values, and phytate-bound P and phytate-bound P relative to total P in the high-phytate diet was greater than in the normal-phytate diet (Table 3). For the Ca- and P-free diets, one growing pig and one sow were identified as outliers and removed from the dataset; one sow fed the high-phytate diet was also identified as an outlier and removed.

3.1. Basal endogenous losses of Ca and P

The basal endogenous loss of Ca was 1.58 g/kg dry matter intake and 0.43 g/kg dry matter intake for gestating sows and growing pigs, respectively, and these values were different ($P < 0.001$; Table 4). The basal endogenous loss of P was 0.78 g/kg dry matter intake from gestating sows and this value was greater ($P = 0.011$) than the basal endogenous loss of P from growing pigs (0.16 g/kg dry matter intake). If corrected for metabolic BW, the basal endogenous losses of Ca and P from gestating sows were greater ($P < 0.05$) compared with growing pigs. However, if corrected for BW, the basal endogenous losses of Ca and P were not different between gestating sows and growing pigs.

3.2. Digestibility and retention of Ca

Feed intake and Ca intake by gestating sows were greater than by growing pigs ($P < 0.001$; Table 5). The ATTD of dry matter was not affected by physiological state, but animals fed the normal-phytate diet had greater ($P < 0.001$) ATTD of dry matter than animals fed the high-phytate diet. Fecal excretion by gestating sows was greater than by growing pigs and the difference was greater if the high-phytate diet was fed than if the normal-phytate diet was provided (physiological state × phytate level interaction, $P < 0.001$). Urine excretion by gestating sows was also greater ($P = 0.027$) than by growing pigs. Gestating sows had greater ($P < 0.001$) fecal Ca output than growing pigs and animals fed the high-phytate diet had greater ($P < 0.001$) fecal Ca output than if the normal-phytate diet was fed. Gestating sows fed the normal-phytate diet had greater urine Ca output than growing pigs fed the same diet, but the urine Ca output was not different between gestating sows and growing pigs fed the high-phytate diet (physiological state × phytate level interaction, $P = 0.024$). Phytate level did not affect the absorbed Ca, ATTD of Ca, STTD of Ca, retained Ca, or Ca retention in gestating sows, but the absorbed Ca, ATTD of Ca, STTD of Ca, retained Ca, and Ca retention were greater if growing pigs were fed the normal-phytate diet than the high-phytate diet (physiological state × phytate level interaction, $P < 0.01$). Regardless of dietary treatment, gestating sows had reduced ($P < 0.001$) digestibility and retention of Ca compared with growing pigs.

Daily basal endogenous loss of Ca expressed as g per day was greater for the high-phytate diet than for the normal-phytate diet if fed to gestating sows, but for growing pigs, no difference between the 2 diets was observed (physiological state × phytate level interaction, $P = 0.031$). However, regardless of dietary treatment, the daily basal endogenous loss of Ca was much greater ($P < 0.001$) in gestating sows than in growing pigs.

3.3. Digestibility and retention of P

Phosphorus intake by gestating sows was greater than by growing pigs and the difference was greater if the high-phytate diet rather than the normal-phytate diet was fed (physiological state × phytate level interaction; $P < 0.001$; Table 6). Fecal P output was greater if the high-phytate diet rather than the normal-phytate diet was fed and the difference was greater for growing pigs than for gestating sows (physiological state × phytate level interaction; $P < 0.001$). Gestating sows absorbed less ($P = 0.036$) P than growing pigs, and the absorbed P was greater ($P = 0.049$) if pigs were fed the normal-phytate diet compared with the high-phytate diet. The ATTD of P was greater if growing pigs were fed the normal-phytate diet rather than the high-phytate diet, but the ATTD of P was not affected by

Table 4
Basal endogenous losses of Ca and P from gestating sows and growing pigs fed Ca-free and P-free diets[a].

Item	Gestating sows	Growing pigs	SED	P-value
Basal endogenous loss, g/kg dry matter intake				
Ca	1.58	0.43	0.12	< 0.001
P	0.78	0.16	0.17	0.011
Basal endogenous loss, g/kg metabolic BW[b]				
Ca	0.51	0.22	0.05	< 0.001
P	0.24	0.08	0.05	0.013
Basal endogenous loss, g/kg BW				
Ca	0.056	0.066	0.010	0.353
P	0.026	0.023	0.006	0.614

[a] Each mean for gestating sows and growing pigs represents 7 replicate animals.
[b] BW = body weight; metabolic BW = $BW^{0.60}$.

Table 5
Apparent total tract digestibility (ATTD) and standardized total tract digestibility (STTD) and retention of Ca in experimental diets fed to gestating sows and growing pigs[1].

Physiological state:	Gestating sows		Growing pigs			P-value[2]		
Phytate:	Normal	High	Normal	High	SEM	State	Phytate	State × Phytate
Initial BW[3], kg	251.9	249.3	19.7	19.8	4.65	< 0.001	0.752	0.743
Feed intake, kg/day	2.67	2.78	1.02	1.05	0.058	< 0.001	0.084	0.308
Fecal excretion, kg/day	0.25[b]	0.51[a]	0.10[c]	0.21[b]	0.014	< 0.001	< 0.001	< 0.001
ATTD of dry matter	0.90	0.82	0.90	0.81	0.005	0.550	< 0.001	0.349
Urine excretion, kg/day	15.84	12.87	4.35	3.94	4.368	0.027	0.701	0.772
Ca intake, g/day	18.66	20.22	7.15	7.65	0.421	< 0.001	0.002	0.063
Fecal Ca output, g/day	17.66	19.02	1.95	4.64	0.740	< 0.001	< 0.001	0.081
Absorbed Ca, g/day	1.00[b]	1.23[b]	5.19[a]	3.01[b]	0.534	0.001	0.011	0.003
ATTD of Ca	0.06[c]	0.06[c]	0.73[a]	0.39[b]	0.030	< 0.001	< 0.001	< 0.001
Basal endogenous Ca loss, g/day	3.75[b]	4.01[a]	0.40[c]	0.42[c]	0.082	< 0.001	0.013	0.031
mg/day/metabolic BW[3]	136[b]	146[a]	66[d]	70[c]	2.08	< 0.001	< 0.001	< 0.001
mg/day/BW	14.90	16.06	20.09	21.21	0.381	< 0.001	< 0.001	0.900
STTD of Ca[4]	0.26[c]	0.26[c]	0.78[a]	0.45[b]	0.030	< 0.001	< 0.001	< 0.001
Urine Ca output, g/day	0.80[a]	0.54[ab]	0.26[b]	0.51[ab]	0.107	0.013	0.976	0.024
Retained Ca, g/day	0.21[b]	0.64[b]	4.94[a]	2.50[b]	0.579	0.001	0.024	0.003
Ca retention, proportion of Ca intake	0.01[c]	0.04[c]	0.69[a]	0.33[b]	0.033	< 0.001	< 0.001	< 0.001

[a-c] Within a row, means without a common superscript differ (P < 0.05).
[1] Each mean for experimental diets from gestating sows and growing pigs represents 8 replicate animals, with the exceptions of the high-phytate diet for gestating sows (n = 7).
[2] State = effect of physiological states; Phytate = effect of phytate level that is normal-phytate or high-phytate in diets.
[3] BW = body weight, kg; metabolic BW = $BW^{0.60}$.
[4] Basal endogenous loss of Ca from gestating sows = 1.58 g/kg dry matter intake; basal endogenous loss of Ca from growing pigs = 0.43 g/kg dry matter intake.

Table 6
Apparent total tract digestibility (ATTD) and standardized total tract digestibility (STTD) and retention of P in experimental diets fed to gestating sows and growing pigs[1].

Physiological state:	Gestating sows		Growing pigs			P-value[2]		
Phytate:	Normal	High	Normal	High	SEM	State	Phytate	State × Phytate
P intake, g/day	16.09[b]	30.36[a]	6.16[d]	11.46[c]	0.553	< 0.001	< 0.001	< 0.001
Fecal P output, g/day	13.53[b]	28.85[a]	2.43[d]	8.49[c]	0.809	< 0.001	< 0.001	< 0.001
Absorbed P, g/day	2.56	1.55	3.73	2.97	0.487	0.036	0.049	0.762
ATTD of P	0.16[bc]	0.05[c]	0.61[a]	0.26[b]	0.030	< 0.001	< 0.001	0.001
Basal endogenous P loss, g/day	1.87[b]	2.00[a]	0.15[c]	0.16[c]	0.041	< 0.001	0.015	0.028
mg/day/metabolic BW[3]	67.67[b]	72.61[a]	24.76[d]	26.18[c]	1.375	< 0.001	< 0.001	< 0.001
mg/day/BW	7.42	7.99	7.52	7.94	0.181	0.928	< 0.001	0.153
STTD of P[4]	0.28[b]	0.12[c]	0.63[a]	0.27[b]	0.030	< 0.001	< 0.001	0.002
Urine P output, g/day	2.39	2.07	0.12	0.19	0.172	< 0.001	0.438	0.221
Retained P, g/day	0.17	-0.51	3.61	2.78	0.467	< 0.001	0.055	0.832
P retention, proportion of P intake	0.01[c]	-0.01[c]	0.59[a]	0.24[b]	0.026	< 0.001	< 0.001	< 0.001

[a-d] Within a row, means without a common superscript differ (P < 0.05).
[1] Each mean for experimental diets from gestating sows and growing pigs represents 8 replicate animals, with the exceptions of the high-phytate diet for gestating sows (n = 7).
[2] State = effect of physiological states; Phytate = effect of phytate level that is normal-phytate or high-phytate in diets.
[3] BW = body weight, kg; metabolic BW = $BW^{0.60}$.
[4]Basal endogenous loss of P from gestating sows = 0.78 g/kg dry matter intake; basal endogenous loss of P from growing pigs = 0.16 g/kg dry matter intake.

dietary treatment if diets were fed to gestating sows (physiological state × phytate level interaction; P = 0.001). Likewise, the STTD of P was greater if pigs were fed the normal-phytate diet rather than the high-phytate diet, but the difference between the 2 diets was greater for growing pigs than for gestating sows (physiological state × phytate level interaction; P = 0.002). Urine P output was greater (P < 0.001) in gestating sows compared with growing pigs and gestating sows retained less (P < 0.001) P compared with growing pigs. Phosphorus retention by growing pigs fed the normal-phytate diet was greater than if pigs were fed the high-phytate diet, but P retention by gestating sows was not affected by phytate level (physiological state × phytate level interaction; P < 0.001). Regardless of dietary treatment, gestating sows had reduced (P < 0.001) digestibility and retention of P compared with growing pigs.

Daily basal endogenous loss of P by gestating sows expressed as g per day was greater for the high-phytate diet than the normal-phytate diet, but for growing pigs, no difference between the 2 diet types was observed (physiological state × phytate level interaction,

P = 0.028). However, regardless of dietary treatment, the daily basal endogenous loss of P was much greater (P < 0.001) from gestating sows than from growing pigs.

4. Discussion

The difference in feed intake between gestating sows and growing pigs was due to differences in BW, but both groups of animals were fed close to what is common in commercial production.

4.1. Digestibility and retention of Ca and P in diets fed to gestating sows

Values for the ATTD of Ca and P in the normal-phytate diet obtained in this study were within the range of values reported for gestating sows fed corn, soybean meal, and inorganic Ca and P-based diets at day 75–105 of gestation (Nyachoti et al., 2006; Jang et al., 2014; Darriet et al., 2017; Lee et al., 2018).

It is likely that the very low retention of Ca and P and the greater urine Ca and P that were observed for gestating sows compared with growing pigs are a result of sows having adequate stores of Ca and P, and therefore, sows had no need for retaining additional Ca and P. Ash contents of bones may be greater in sows than in gilts, indicating that sows accumulate Ca and P in bones over time (Giesemann et al., 1998). A model that calculates the P requirement for gestating sows indicates that requirements are very low in multiparous sows until mid-gestation and almost no P is needed by the fetuses (Bikker and Blok, 2017). However, the requirement increases in late gestation, which coincides with increased digestibility and retention of Ca and P (Lee et al., 2019a).

4.2. Digestibility and retention of Ca and P in diets fed to growing pigs

Values for the ATTD and STTD of Ca and P in the normal-phytate diet were in agreement with reported values (Almeida et al., 2013; González-Vega et al., 2016; Stein et al., 2016). The ATTD and STTD of Ca and P in the high-phytate diet were also within the range of reported values (Trujillo et al., 2010; Casas and Stein, 2015; Lucca et al., 2017). The basal endogenous loss of Ca obtained from growing pigs was in agreement with data from other studies in which a corn-based Ca-free diet was used (González-Vega et al., 2015b; Merriman and Stein, 2016; Blavi et al., 2017) and the basal endogenous loss of P also concurred with reported values for the basal endogenous loss of P (NRC, 2012). Values for the retention of Ca and P that were expressed as g/d also were in agreement with published data (Mroz et al., 1994; González-Vega et al., 2016). However, the retention of Ca and P (as proportion of intake) varied between diets and also varies among previous experiments, which most likely is because the body will reduce retention if intake exceeds the requirement for Ca and P (Symeou et al., 2014; González-Vega et al., 2016).

4.3. Effect of phytate on Ca and P balance

The observation that the digestibility of Ca and P in the high-phytate diet fed to growing pigs was lower than in the normal-phytate diet is likely a result of the reduced level of dicalcium phosphate and the greater level of calcium carbonate and phytate in the high-phytate diet compared with the normal-phytate diet. Phytate-P is less likely to be absorbed because pigs do not secrete sufficient phytase to liberate P from phytate, and as a consequence, P digestibility in feed ingredients containing greater amounts of phytate-P is relatively lower compared with ingredients containing less phytate-P. The digestibility of Ca in dicalcium phosphate is greater than in calcium carbonate (González-Vega et al., 2015a) and, therefore, an increase in the proportion of Ca from calcium carbonate in the diet may have contributed to reduced digestibility of Ca in the high-phytate diet. Phytate binds positively charged ions including Ca^{2+} because of the negatively charged reactive sites on the phytate molecule, which may result in chelated Ca-phytate complexes (Selle et al., 2009). Unlike Ca in monocalcium phosphate or dicalcium phosphate, Ca from calcium carbonate may chelate phytate molecules (González-Vega et al., 2015a), and if more calcium carbonate is used in the diet, the digestibility of not only Ca, but also P, may be reduced. As a consequence, it was expected that the STTD of Ca in the high-phytate diet would be less than in the normal phytate diet due to the increased proportion of Ca from Ca carbonate and the greater binding of Ca to phytate in the high-phytate diet.

The observed interactions between the physiological state and phytate level for the STTD of Ca and P and Ca and P retention indicated that growing pigs were more likely to be affected by dietary phytate than gestating sows. A negative correlation between digestibility of Ca and P and dietary phytate by growing pigs was also reported in the past (Almaguer et al., 2014; Lee et al., 2018). Likewise, insoluble fiber or phytate in diets may decrease the absorption of Ca or P due to reduced transit time in the gut (Nortey et al., 2007; Hill et al., 2008). It is, therefore, possible that the insoluble fiber in rice bran decreased the absorption of Ca and P in growing pigs. However, it is not clear why gestating sows and growing pigs have different responses to dietary phytate for Ca and P digestibility and retention in the body. It is also possible that the response to the insoluble fiber is reduced in gestating sows because the passage rate in the gastrointestinal tract of gestating sows is slower compared with growing pigs. It is also possible that because the STTD of Ca and P in gestating sows was already very low, the addition of more phytate, and therefore more phytate-bound P and Ca, did not hinder sows from absorbing the small amounts of Ca and P that they needed and it can be speculated that the phytate and fiber effects are only evident when an animal needs the marginally soluble Ca and P that is bound to phytate. However, further research investigating factors affecting digestion and retention of Ca and P in gestating sows is needed.

4.4. Comparative digestibility and retention of Ca and P in gestating sows and growing pigs

The basal endogenous losses of Ca and P were in agreement with values previously reported for sows in mid-gestation (Bikker et al., 2017; Lee et al., 2019a). The observation that the basal endogenous loss of P was greater in sows compared with growing pigs is in agreement with published data, which may be a result of differences in body size of pigs rather than differences in dry matter intake (Bikker et al., 2017). Because the BW of sows was approximately 10 times greater than the BW of growing pigs, the basal endogenous losses of Ca and P per kg BW between sows and growing pigs were not different. It is, however, necessary to express endogenous losses on the basis of dry matter intake to be able to use the values in diet formulation, which is the reason values for STTD of Ca and P need to be calculated.

The observation that the ATTD of Ca and P in growing pigs is greater than in sows concurs with reported data (Kemme et al., 1997; Lee et al., 2018). However, to our knowledge, no comparative values for the STTD of Ca and P or the basal endogenous losses of Ca and P between gestating sows and growing pigs have been reported. It is unlikely that the difference in feed intake is the main reason for this difference because feed intake of sows does not affect digestibility of Ca and P (Lee et al., 2018). The greater endogenous losses of Ca and P from gestating sows than from growing pigs will result in reduced ATTD of Ca and P in sows compared with growing pigs. However, the current results indicate that digestibility of Ca and P in gestating sows is much less than in growing pigs, even if values are corrected for the greater basal endogenous losses of Ca and P as is the case when STTD values are calculated. Differences in the basal endogenous losses, therefore, do not explain the differences in STTD values between growing pigs and sows, but the present data indicate that there are physiological differences that result in differences in ATTD and STTD of Ca and P. It is possible that this is related to the fact that gestating sows have a requirement for Ca and P that is close to the maintenance requirement whereas growing pigs have a requirement for growth and bone development in addition to the requirement for maintenance (NRC, 2012; Bikker and Blok, 2017). However, additional research is needed to address this hypothesis.

5. Conclusion

Gestating sows have reduced digestibility and retention of Ca and P, but increased basal endogenous losses of Ca and P (g/kg dry matter intake), compared with growing pigs. If calculated as g per kg BW, there were no differences in the basal endogenous losses of Ca and P between growing pigs and gestating sows. Gestating sows also respond differently to dietary phytate concentration than do growing pigs. As a consequence, it may not always be accurate to formulate diets for gestating sows using apparent total tract digestibility or standardized total tract digestibility values for Ca and P that were obtained in growing pigs.

Conflict of interest

The authors have no conflicts of interest.

Acknowledgements

Financial support for this research from AB Vista, Marlborough, SN8 4AN, United Kingdom, is greatly appreciated.

References

Adeola, O., 2001. Digestion and balance techniques in pigs. In: Lewis, A.J., Southern, L.L. (Eds.), Swine Nutrition. CRC Press, Washington, DC, USA, pp. 903–916.
Almaguer, B.L., Sulabo, R.C., Liu, Y., Stein, H.H., 2014. Standardized total tract digestibility of phosphorus in copra meal, palm kernel expellers, palm kernel meal, and soybean meal fed to growing pigs. J. Anim. Sci. 92, 2473–2480.
Almeida, F.N., Stein, H.H., 2010. Performance and phosphorus balance of pigs fed diets formulated on the basis of values for standardized total tract digestibility of phosphorus. J. Anim. Sci. 88, 2968–2977.
Almeida, F.N., Sulabo, R.C., Stein, H.H., 2013. Effects of a novel bacterial phytase expressed in Aspergillus Oryzae on digestibility of calcium and phosphorus in diets fed to weanling or growing pigs. J. Anim. Sci. Biotechnol. 4, 8.
AOAC Int., 2007. Official methods of analysis of AOAC Int. AOAC Int., Gaithersburg, MD, USA.
Bikker, P., Blok, M., 2017. Phosphorus and calcium requirements of growing pigs and sows. Wageningen Livestock Research CVB documentation report 59.
Bikker, P., van der Peet-Schwering, C.M.C., Gerrits, W.J.J., Sips, V., Walvoort, C., van Laar, H., 2017. Endogenous phosphorus losses in growing-finishing pigs and gestating sows. J. Anim. Sci. 95, 1637–1643.
Blavi, L., Sola-Oriol, D., Perez, J.F., Stein, H.H., 2017. Effects of zinc oxide and microbial phytase on digestibility of calcium and phosphorus in maize-based diets fed to growing pigs. J. Anim. Sci. 95, 847–854.
Casas, G.A., Stein, H.H., 2015. Effects of microbial phytase on the apparent and standardized total tract digestibility of phosphorus in rice coproducts fed to growing pigs. J. Anim. Sci. 93, 3441–3448.
Casas, G.A., Stein, H.H., 2017. Gestating sows have greater digestibility of energy in full fat rice bran and defatted rice bran than growing gilts regardless of level of feed intake. J. Anim. Sci. 95, 3136–3142.
Darriet, C., Axe, D.E., Crenshaw, T.D., 2017. Acidogenic mineral additions increased Ca mobilization in prepartum sows. J. Anim. Sci. 95, 212–225.
Giesemann, M.A., Lewis, A.J., Miller, P.S., Akhter, M.P., 1998. Effects of the reproductive cycle and age on calcium and phosphorus metabolism and bone integrity of sows. J. Anim. Sci. 76, 796–807.
González-Vega, J.C., Walk, C.L., Stein, H.H., 2015a. Effects of microbial phytase on apparent and standardized total tract digestibility of calcium in calcium supplements fed to growing pigs. J. Anim. Sci. 93, 2255–2264.
González-Vega, J.C., Walk, C.L., Stein, H.H., 2015b. Effect of phytate, microbial phytase, fiber, and soybean oil on calculated values for apparent and standardized total tract digestibility of calcium and apparent total tract digestibility of phosphorus in fish meal fed to growing pigs. J. Anim. Sci. 93, 4808–4818.
González-Vega, J.C., Liu, Y., McCann, J.C., Walk, C.L., Loor, J.J., Stein, H.H., 2016. Requirement for digestible calcium by eleven- to twenty-five-kilogram pigs as determined by growth performance, bone ash concentration, calcium and phosphorus balances, and expression of genes involved in transport of calcium in intestinal and kidney cells. J. Anim. Sci. 94, 3321–3334.

Hill, G.M., Link, J.E., Rincker, M.J., Kirkpatrick, D.L., Gibson, M.L., Karges, K., 2008. Utilization of distillers dried grains with solubles and phytase in sow lactation diets to meet the phosphorus requirement of the sow and reduce fecal phosphorus concentration. J. Anim. Sci. 86, 112–118.
Jang, Y.D., Lindemann, M.D., van Heugten, E., Jones, R.D., Kim, B.G., Maxwell, C.V., Radcliffe, J.S., 2014. Effects of phytase supplementation on reproductive performance, apparent total tract digestibility of Ca and P and bone characteristics in gestating and lactating sows. Rev. Colomb. Cienc. Pecu. 27, 178–193.
Kemme, P.A., Jongbloed, A.W., Mroz, Z., Beynen, A.C., 1997. The efficacy of *Aspergillus niger* phytase in rendering phytate phosphorus available for absorption in pigs is influenced by pig physiological status. J. Anim. Sci. 75, 2129–2138.
Le Goff, G., Noblet, J., 2001. Comparative total tract digestibility of dietary energy and nutrients in growing pigs and adult sows. J. Anim. Sci. 79, 2418–2427.
Lee, S.A., Casas, G.A., Stein, H.H., 2018. The level of feed intake does not influence digestibility of calcium and phosphorus in diets fed to gestating sows, but gestating sows have reduced digestibility of calcium and phosphorus compared with growing gilts. Can. J. Anim. Sci. 98, 591–594.
Lee, S.A., Lagos, L.V., Walk, C.L., Stein, H.H., 2019a. Basal endogenous loss, standardized total tract digestibility of calcium in calcium carbonate, and retention of calcium in gestating sows change during gestation, but microbial phytase reduces basal endogenous loss of calcium. J. Anim. Sci. 97, 1712–1721.
Lee, S.A., Lagos, L.V., Walk, C.L., Stein, H.H., 2019b. Standardized total tract digestibility of calcium varies among sources of calcium carbonate, but not among sources of dicalcium phosphate, but microbial phytase increases calcium digestibility in calcium carbonate. J. Anim. Sci. 97, 3440–3450.
Lucca, W., Ceron, M.S., Lucca, M.S., Casagrande, L.G., da Rocha, L.T., Zanella, I., de Oliveira, V., 2017. Effect of phytase on true total tract digestibility of phosphorus in full-fat rice bran determined in pigs by regression method. Turk. J. Vet. Anim. Sci. 41, 490–495.
Merriman, L.A., Stein, H.H., 2016. Particle size of calcium carbonate does not affect apparent and standardized total tract digestibility of calcium, retention of calcium, or growth performance of growing pigs. J. Anim. Sci. 94, 3844–3850.
Mroz, Z., Jongbloed, A.M., Kemme, P.A., 1994. Apparent digestibility and retention of nutrients bound to phytate complexes as influenced by microbial phytase and feeding regimen in pigs. J. Anim. Sci. 72, 126–132.
Nortey, T.N., Patience, J.F., Simmins, P.H., Trottier, N.L., Zijlstra, R.T., 2007. Effects of individual or combined xylanase and phytase supplementation on energy, amino acid, and phosphorus digestibility and growth performance of grower pigs fed wheat-based diets containing wheat millrun. J. Anim. Sci. 85, 1432–1443.
NRC, 2012. Nutrient Requirements of Swine, eleventh rev. ed. Natl. Acad. Press, Washington, DC, USA.
Nyachoti, C.M., Sands, J.S., Connor, M.L., Adeola, O., 2006. Effect of supplementing phytase to corn- or wheat-based gestation and lactation diets on nutrient digestibility and sow and litter performance. Can. J. Anim. Sci. 86, 501–510.
Petersen, G.I., Stein, H.H., 2006. Novel procedure for estimating endogenous losses and measurement of apparent and true digestibility of phosphorus by growing pigs. J. Anim. Sci. 84, 2126–2132.
SAS, 2018. SAS/STAT®, User's Guide, Version 15.1. SAS Institute Inc, Cary, NC, USA.
Selle, P.H., Cowieson, A.J., Ravindran, V., 2009. Consequences of calcium interactions with phytate and phytase for poultry and pigs. Livest. Sci. 124, 126–141.
Stein, H.H., Merriman, L.A., González-Vega, J.C., 2016. Establishing a digestible calcium requirement for pigs. In: Walk, C.L., Kühn, I., Stein, H.H., Kidd, M.T., Rodehutscord, M. (Eds.), Phytate Destruction - Consequences for Precision Animal Nutrition. Wageningen Academic Publishers, Wageningen, the Netherlands, pp. 207–216.
Symeou, V., Leinonen, I., Kyriazakis, I., 2014. Modelling phosphorus intake, digestion, retention and excretion in growing and finishing pigs: model description. Animal 8, 1612–1621.
Tran, G., Sauvant, D., 2004. Chemical data and nutritional value. In: Ponter, A., Sauvant, D., Perez, J.-M., Tran, G. (Eds.), Tables of Composition and Nutritional Value of Feed Materials: Pigs, Poultry, Cattle, Sheep, Goats, Rabbits, Horses and Fish. Wageningen Academic Publishers, Wageningen, the Netherlands, pp. 17–24.
Trujillo, J.H.A., Lindemann, M.D., Cromwell, G.L., 2010. Phosphorus utilization in growing pigs fed a phosphorus deficient diet supplemented with a rice bran product and amended with phytase. Rev. Colomb. Cienc. Pecu. 23, 429–443.
Tukey, J.W., 1977. Exploratory Data Analysis. Addison-Wesley Pub, Co., Boston, MA, USA.
Zhang, F., Ragland, D., Adeola, O., 2016. Comparison of apparent ileal and total tract digestibility of calcium in calcium sources for pigs. Can. J. Anim. Sci. 96, 563–569.
Zhang, F., Adeola, O., 2017. True is more additive than apparent total tract digestibility of calcium in limestone and dicalcium phosphate for twenty-kilogram pigs fed semipurified diets. J. Anim. Sci. 95, 5466–5473.