Effects of microbial phytase on standardized total tract digestibility of phosphorus in hybrid rye, barley, wheat, corn, and sorghum fed to growing pigs[1]

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ABSTRACT: An experiment was conducted to determine the apparent total tract digestibility (ATTD) and the standardized total tract digestibility (STTD) of P in three varieties of hybrid rye and in one source of barley, wheat, corn, and sorghum. The STTD of P in each cereal grain was determined both without and with addition of microbial phytase. In total, 112 growing barrows (13.7 ± 1.3 kg initial BW) were allotted to a randomized complete block design with four blocks of 28 pigs. Pigs were randomly allotted to 14 diets with two replicate pigs per diet in each block, resulting in a total of eight replicate pigs per diet for the four blocks. Each diet contained one of the cereal grains as the sole source of P. There were two diets with each cereal grain with one diet containing no microbial phytase and the other diet containing 1,000 units of microbial phytase per kilogram of diet. In each period, fecal output was collected for 5 d following a 5-d adaptation period according to the marker-to-marker procedure. Among the diets that did not include microbial phytase, one hybrid of rye had greater ($P < 0.05$) STTD of P than wheat, corn, and sorghum, which is likely a result of the greater intrinsic phytase activity in rye than in the other cereal grains. Without microbial phytase, there was no difference in the STTD of P in the three hybrids of rye and barley. Among the diets containing microbial phytase, there was no difference in STTD of P among the three hybrids of rye, barley, and corn. The STTD of P in the three hybrids of rye with microbial phytase was 61.9%, 70.8%, and 63.0%, respectively. Overall, microbial phytase improved ($P < 0.05$) the STTD of P in all cereal grains, although the magnitude of the increase in STTD of P differed among the grains.

INTRODUCTION

In Europe and North America, rye is primarily grown for the bread making, biogas, beverage, and livestock feed industries. Recently, hybrid varieties of rye became commercially available, and compared with conventional rye, hybrid rye has increased crop yield and reduced risk of ergot contamination (Jürgens et al., 2012; Miedaner and Geiger, 2015), which makes hybrid rye more suitable for livestock feed than older cultivars of rye. However, there is limited data for the nutritional value of hybrid rye when fed to pigs. Previous research with hybrid rye has focused on the digestibility of AA (Strang et al., 2016; McGhee and Stein, 2018), but to our knowledge, there are no published data for the digestibility of P in pigs fed hybrid rye.

Cereal grains have a high percentage of total P bound to phytic acid (Nelson et al., 1968), which is not digested well by pigs, but addition of microbial phytase to diets increases the digestibility of P

(Maga, 1982). Rye has high levels of intrinsic phytase (Rodehutscord et al., 2016), which may result in increased digestibility of P by pigs (Pointillart et al., 1987). It is, therefore, possible that the response to microbial phytase in hybrid rye is different from other cereal grains, but this hypothesis has not been experimentally tested. The objective of this experiment, therefore, was to test the hypothesis that the apparent total tract digestibility (ATTD) and the standardized total tract digestibility (STTD) of P in hybrid rye are greater than in corn, barley, wheat, and sorghum, and that addition of microbial phytase increases ATTD and STTD of P in all cereal grains.

MATERIALS AND METHODS

The experiment was conducted at the Swine Research Center at the University of Illinois following a protocol that was approved by the Institutional Animal Care and Use Committee at the University of Illinois.

Animals, Housing, and Experimental Design

Three hybrids of rye (KWS Lochow GmbH, Bergen, Germany) and one source of barley, wheat, corn, and sorghum, all of which were grown in 2016, were used in the experiment. The three hybrids of rye included two hybrids that were grown in Germany and one hybrid that was grown in Canada. The barley, wheat, corn, and sorghum used in the experiment were grown in the United States. Grains were ground using a hammer mill to a mean particle size of ~300 μm, and each grain was used in two diets. Seven diets contained each hybrid of rye or barley, wheat, corn, or sorghum in addition to sucrose, soybean oil, vitamins, and minerals (Table 1). No inorganic P was added to the diets, and all P in the diets, therefore, originated from the cereal grains. Limestone was included in each diet to maintain an overall Ca concentration of 0.4%. Seven additional diets that were similar to the initial seven diets with the exception that they contained 1,000 units of microbial phytase (Quantum Blue 5G; AB Vista, Marlborough, UK) per kilogram of diet were also formulated.

In total, 112 growing barrows (13.7 ± 1.3 kg initial BW) that were the offspring of Line 359 boars and Camborough sows (Pig Improvement Company, Henderson, TN) were allotted to a randomized complete block design with four blocks of 28 pigs. Within each block, the 28 pigs were randomly allotted to the 14 diets with two replicate pigs per diet, resulting in a total of eight replicate pigs per diet for the four blocks.

Feeding and Sample Collection

Pigs were housed in individual metabolism crates that were equipped with a feeder, a nipple waterer, and fully slatted metal floors. A screen floor was placed under the slatted floor to allow for the total collection of fecal materials. Pigs were fed at 3.0 times the estimated ME requirement for maintenance (i.e., 197 kcal ME per kg $BW^{0.60}$; NRC, 2012), which was provided each day in two equal meals at 0800 and 1600 hours. Water was available on an *ad libitum* basis. Feed consumption was recorded daily, and pigs were fed experimental diets for 12 d, with the initial 5 d being an adaptation period to the diets, and the following 5 d being used for total collection of feces according to the marker-to-marker procedure (Adeola, 2001).

Chemical Analyses

Fecal samples were stored at −20 °C immediately after collection. At the conclusion of the

Table 1. Ingredient composition of experimental diets[1]

Ingredient, %	Rye 1	Rye 2	Rye 3	Barley	Wheat	Corn	Sorghum
Cereal grain	84.35	84.35	84.35	84.35	84.35	84.25	84.25
Sucrose	10.00	10.00	10.00	10.00	10.00	10.00	10.00
Soybean oil	4.00	4.00	4.00	4.00	4.00	4.00	4.00
Limestone	0.95	0.95	0.95	0.95	0.95	1.05	1.05
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin–mineral premix[2]	0.30	0.30	0.30	0.30	0.30	0.30	0.30

[1]For each ingredient, an additional diet was prepared by including microbial phytase (Quantum Blue 5G; AB Vista, Marlborough, UK) at a level of 1,000 phytase units per kilogram diet (0.02%) at the expense of cereal grain. Thus, a total of 14 diets were prepared with the seven cereal grains.

[2]The vitamin–micro mineral premix provided the following quantities of vitamins and micro minerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as DL-α 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 and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

experiment, fecal samples were dried in a forced air oven and ground using a 1-mm screen in a Wiley mill (model 4, Thomas Scientific, Swedesboro, NJ). Samples of diets, ingredients, and fecal materials were analyzed for DM, Ca, and P. The DM of samples was determined by oven drying at 135 °C for 2 h (method 930.15; AOAC International, 2007). Calcium and total P were measured by inductively coupled plasma optical emission spectroscopy (method 985.01 A, B, and C; AOAC International, 2007) after wet ash sample preparation (method 975.03 B(b); AOAC International, 2007). Ingredient samples were analyzed for Cu, K, Mg, Mn, and Zn using the same procedure, and concentrations of Fe, Na, and Se were also determined using inductively coupled plasma optical emission spectroscopy (method 990.08; AOAC International, 2007). The concentration of S was determined by gravimetric analysis (method 956.01; AOAC International, 2007). The concentration of Cl was determined by manual titration (method 943.01; AOAC International, 2007), and the concentration of I was determined by volumetric analysis (method 935.14; AOAC International, 2007). Diet and ingredient samples were analyzed for dry ash (method 942.05; AOAC International, 2007). The GE in diets was measured using an isoperibol bomb calorimeter (model 6400, Parr Instruments, Moline, IL). Benzoic acid was used as the standard for calibration. The crude protein (CP) in diets was determined by measuring N (method 990.03; AOAC International, 2007) using a Leco Nitrogen Determinator (model FP628, Leco Corp., St. Joseph, MI). Diets and ingredients were analyzed for phytase activity (Phytex Method, Version 1; Eurofins, Des Moines, IA), and all ingredients were analyzed for phytic acid (Ellis et al., 1977). The phytic acid concentration in the diets was calculated using the phytic acid concentration in the ingredients. Phytate-bound P in diets and ingredients was calculated as 28.2% of phytic acid (Sauvant et al., 2004), and nonphytate P was calculated as total P (%) minus phytate-bound P (%).

Calculations and Statistical Analysis

The ATTD of P was calculated for each diet using the following equation (Almeida and Stein, 2010):

$$\text{ATTD} \quad (\%) = \left[\frac{P_i - P_f}{P_i} \right] \times 100$$

where P_i is the total P intake (g) from days 6 to 10 and P_f is the total fecal P output (g) originating from the feed that was provided from days 6 to 10. The same equation was used to calculate the ATTD of Ca.

The STTD of P was calculated using the following equation (NRC, 2012):

$$\text{STTD} \quad (\%) = \left[\frac{P_i - (P_f - \text{EPL})}{P_i} \right] \times 100$$

where EPL is the basal endogenous loss of P. A basal endogenous loss of P of 190 mg per kg DM intake was assumed for all pigs (NRC, 2012), and this value was used to calculate the STTD of P in all diets.

Data were analyzed using the MIXED Procedure of SAS (SAS Institute Inc., Cary, NC). The pig was the experimental unit for all analyses. An outlier was defined as an observation with a studentized residual of >3 or < −3 and was subsequently removed from further statistical analysis. PROC UNIVARIATE and PROC GPLOT were used to check model assumptions on the residuals. The model included ingredient source, level of phytase, and the interaction between ingredient and level of phytase as fixed effects and block and replicate within block as random effects. Least squares means were estimated and separated using the LSMEANS statement with PDIFF (P-values for differences of least squares means) option and Tukey–Kramer adjustment in PROC MIXED. Results were considered significant at $P \le 0.05$ and considered a trend at $P \le 0.10$.

RESULTS

All pigs consumed their diets throughout the experiment without apparent problems. The GE in the diets ranged from 3,956 to 4,082 kcal/kg, and the CP in the diets ranged from 6.22% in one of the corn diets to 9.38% in one of the wheat diets (Table 2). The concentration of ash in the diets ranged from 2.34% to 2.96%, and the concentration of ash in the ingredients ranged from 1.21% to 1.76% (Table 3). Rye, barley, and wheat contained ~0.03% Ca, whereas both corn and sorghum contained 0.01% Ca. The concentration of total P was numerically greatest in wheat (0.36%) and numerically least in corn (0.23%). The three hybrids of rye contained 0.26%, 0.29%, and 0.32% total P. Barley contained the most nonphytate P (0.09%), followed by wheat, sorghum, and rye, which contained 0.06% to 0.08%, and corn contained only 0.04% nonphytate P. The three hybrids of rye had intrinsic phytase activities ranging from 2,300 to 3,200 phytase units per

Table 2. Composition of experimental diets containing three sources of hybrid rye, barley, wheat, corn, or sorghum, without or with microbial phytase, as-fed basis

Diet	DM, %	GE, kcal/kg	CP, %	Ash, %	Ca, %	P, %	Phytate[1], %	Phytate P[2], %	Nonphytate P[3], %	Phytase, FTU[4]
Without phytase										
Rye 1	90.24	3,956	7.36	2.69	0.42	0.24	0.60	0.17	0.11	1,900
Rye 2	90.64	3,972	7.79	2.80	0.43	0.30	0.74	0.21	0.10	2,200
Rye 3	90.18	3,976	7.75	2.87	0.43	0.27	0.66	0.19	0.10	1,300
Barley	91.26	4,015	8.42	2.64	0.44	0.26	0.54	0.15	0.12	270
Wheat	92.27	4,038	9.38	2.90	0.47	0.35	0.84	0.24	0.14	400
Corn	90.94	4,046	6.22	2.34	0.48	0.22	0.56	0.16	0.06	<70
Sorghum	90.80	4,082	8.32	2.63	0.42	0.24	0.62	0.17	0.07	<70
With phytase, 1,000 FTU										
Rye 1	90.47	3,975	7.65	2.93	0.41	0.22	0.60	0.17	0.09	3,100
Rye 2	90.89	3,967	8.01	2.88	0.41	0.28	0.74	0.21	0.10	3,700
Rye 3	90.26	3,973	7.71	2.96	0.43	0.26	0.66	0.19	0.08	3,000
Barley	92.02	4,031	8.89	2.57	0.39	0.24	0.54	0.15	0.11	1,700
Wheat	92.40	4,026	9.29	2.84	0.42	0.31	0.84	0.24	0.05	1,400
Corn	91.23	4,035	6.27	2.66	0.43	0.20	0.56	0.16	0.06	1,000
Sorghum	90.92	4,081	8.90	2.70	0.44	0.23	0.62	0.17	0.07	610

[1]Phytate concentration in the diets was calculated using the phytate concentration in the ingredients.

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

[3]Nonphytate P was calculated as total P (%) minus phytate-bound P (%).

[4]Phytase expressed as phytase units (FTU) per kilogram of diet.

Table 3. Composition of three sources of hybrid rye, barley, wheat, corn, and sorghum, as-fed basis

Item	Rye 1	Rye 2	Rye 3	Barley	Wheat	Corn	Sorghum
DM, %	87.56	88.15	87.19	88.17	87.85	88.10	89.63
GE, kcal/kg	3,763	3,797	3,772	3,829	3,867	3,874	3,936
CP, %	8.65	9.08	8.90	10.54	11.35	7.20	10.19
Ash, %	1.48	1.55	1.46	1.34	1.76	1.21	1.44
Macro minerals[1], %							
Ca	0.03	0.03	0.03	0.03	0.03	0.01	0.01
K	0.44	0.42	0.40	0.31	0.43	0.36	0.29
Mg	0.10	0.10	0.11	0.09	0.13	0.08	0.11
P	0.26	0.32	0.29	0.27	0.36	0.23	0.28
S	0.11	0.12	0.11	0.14	0.14	0.09	0.11
Micro minerals[1], mg/kg							
Cu	0.48	0.42	0.95	0.94	1.12	<0.10	3.14
Fe	28.20	25.00	31.40	25.30	37.80	17.30	32.00
Mn	16.90	22.00	13.90	10.90	37.70	3.64	12.10
Zn	23.30	23.20	27.00	24.10	27.80	18.20	17.20
Phytate, %	0.71	0.88	0.78	0.64	0.99	0.66	0.73
Phytate-bound P[2], %	0.20	0.25	0.22	0.18	0.28	0.19	0.21
Nonphytate P[3], %	0.06	0.07	0.07	0.09	0.08	0.04	0.07
Phytase, FTU[4]	3,000	3,200	2,300	490	580	<70	80

[1]Cl, Na, Se, and I were analyzed but were not detected. The detectable limit was 0.10% for Cl, 0.01% for Na, 20 mg/kg for Se, and 100 mg/kg for I.

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

[3]Nonphytate P was calculated as total P (%) minus phytate-bound P (%).

[4]Intrinsic phytase expressed as phytase units (FTU) per kilogram of diet.

kilogram. In comparison, the intrinsic phytase activity of wheat and barley was 580 and 490 phytase units per kilogram, respectively, and corn and sorghum had less than 100 phytase units per kilogram intrinsic phytase activity.

There was no source by phytase interaction for ADFI nor fecal output (Table 4). There was no effect of microbial phytase on feed intake, but differences ($P < 0.05$) among cereal grains were observed. There was a tendency ($P < 0.10$) for pigs

Table 4. Daily feed and P intake, ATTD, and STTD of P in experimental diets

Treatment	Feed intake, g/d	Fecal output, g/d	P intake, g/d	P in feces, %	P output, g/d	ATTD of P, %	STTD of P, %
Without phytase							
Rye 1	640	77.5	1.41	1.09[cde]	0.84[bc]	40.9[efg]	48.7[de]
Rye 2	579	70.0	1.57	1.16[bcd]	0.79[bcd]	49.1[bcdef]	55.5[bcd]
Rye 3	535	63.8	1.34	1.28[bc]	0.78[bcd]	41.9[defg]	48.8[de]
Barley	605	50.0	1.39	1.79[a]	0.87[abc]	37.0[fg]	44.6[de]
Wheat	446	52.5	1.38	1.91[a]	0.99[ab]	31.0[g]	36.6[ef]
Corn	572	51.4	1.15	1.85[a]	0.94[ab]	16.3[h]	24.9[fg]
Sorghum	519	58.8	1.19	1.97[a]	1.13[a]	9.5[h]	17.0[g]
With phytase, 1,000 FTU[2]							
Rye 1	546	61.3	1.20	0.90[e]	0.56[def]	54.1[abcd]	61.9[abc]
Rye 2	661	75.0	1.79	0.86[e]	0.63[cdef]	64.4[a]	70.8[a]
Rye 3	520	60.0	1.30	0.96[de]	0.57[def]	56.1[abc]	63.0[abc]
Barley	554	40.0	1.28	1.21[bcd]	0.48[f]	60.2[ab]	67.8[ab]
Wheat	501	53.8	1.56	1.38[b]	0.74[bcde]	51.9[abcde]	57.6[bcd]
Corn	563	47.5	1.12	1.07[cde]	0.51[ef]	53.8[abcde]	62.5[abc]
Sorghum	505	55.0	1.16	1.10[cde]	0.62[cdef]	46.1[cdef]	53.6[cd]
SEM	37.97	4.88	0.09	0.06	0.06	3.57	3.57
P-value							
Grain	0.002	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Phytase	0.739	0.088	0.975	<0.001	<0.001	<0.001	<0.001
Interaction	0.251	0.402	0.217	<0.001	0.010	<0.001	<0.001

[a–h] Means in a column without a common superscript differ ($P < 0.05$).

[1] STTD of P was calculated by correcting ATTD of P for basal endogenous losses of P. A basal endogenous loss of P of 190 mg/kg DM intake was assumed for all pigs (NRC, 2012).

[2] Phytase expressed as phytase units (FTU) per kilogram of diet.

to have reduced fecal output if they were fed diets with microbial phytase compared with pigs fed diets without microbial phytase, and grain source also affected ($P < 0.05$) fecal output. There was no source by phytase interaction for P intake, and there was no effect of microbial phytase on P intake; however, differences ($P < 0.05$) in P intake among cereal grains were observed.

There were interactions ($P < 0.05$) between grain source and phytase for the concentration of P in feces, total P output, ATTD of P, and STTD of P, but all interactions were due to differences in the magnitude, rather than in the direction, of the response to phytase. With the exception of the first source of hybrid rye, pigs fed diets containing microbial phytase had lower ($P < 0.05$) concentration of P in feces than pigs fed diets without microbial phytase. Total P output was reduced ($P < 0.05$) for the first source of hybrid rye, and for barley, corn, and sorghum if microbial phytase was added to the diets. Among pigs fed diets without microbial phytase, pigs fed diets containing barley, wheat, corn, and sorghum had greater ($P < 0.05$) concentrations of P in feces than pigs fed the three hybrids of rye. If microbial phytase was added to the diets, pigs fed wheat also had greater concentration of P in feces ($P < 0.05$) than pigs fed any of the hybrids of rye.

The ATTD and STTD of P were greater ($P < 0.05$) in diets containing microbial phytase compared with diets without microbial phytase for all cereal grains. Among diets without microbial phytase, the STTD of P was greater ($P < 0.05$) in the three hybrids of rye than in corn and sorghum, and the STTD of P in the second hybrid of rye was also greater ($P < 0.05$) than in wheat. There was no difference in ATTD or STTD of P between diets containing hybrid rye and the diet containing barley if no microbial phytase was used. For diets containing microbial phytase, there was no difference in ATTD and STTD of P among the three hybrids of rye, barley, or corn, but the second hybrids of rye had greater ($P < 0.05$) STTD of P than wheat and sorghum.

There was no grain source by phytase interaction, nor an effect of phytase, on daily Ca intake, but differences ($P < 0.05$) among grain sources were observed (Table 5). There were interactions ($P < 0.05$) for the concentration of Ca in feces, total fecal Ca output, and ATTD of Ca. The interactions were due to differences in the magnitude of the response to phytase among the grain sources.

Table 5. Daily Ca intake and ATTD of Ca in experimental diets

Treatment	Ca intake, g/d	Ca in feces, %	Ca output, g/d	ATTD of Ca, %
Without phytase				
Rye 1	2.50	0.89[cde]	0.68[abc]	72.8[cde]
Rye 2	2.32	0.81[cde]	0.56[bcd]	76.1[abcd]
Rye 3	2.15	1.01[bc]	0.56[bcd]	70.7[def]
Barley	2.36	1.35[ab]	0.69[abc]	71.8[cdef]
Wheat	1.78	0.94[cd]	0.49[cd]	74.4[def]
Corn	2.35	1.69[a]	0.86[a]	62.9[ef]
Sorghum	2.17	1.41[a]	0.75[ab]	64.9[f]
With phytase, 1,000 FTU[1]				
Rye 1	2.13	0.86[cde]	0.52[bcd]	75.3[abcd]
Rye 2	2.65	0.56[e]	0.41[d]	84.6[a]
Rye 3	2.07	0.64[de]	0.39[d]	81.5[abc]
Barley	2.17	0.81[cde]	0.32[d]	84.8[a]
Wheat	2.02	0.64[de]	0.33[d]	83.2[ab]
Corn	2.30	1.06[bc]	0.45[cd]	77.8[abcd]
Sorghum	2.12	0.96[cd]	0.54[bcd]	74.5[bcd]
SEM	0.15	0.07	0.05	1.85
P-value				
Grain	0.006	<0.001	<0.001	<0.001
Phytase	0.784	<0.001	<0.001	<0.001
Interaction	0.251	<0.001	0.032	0.022

[a–f] Means in a column without a common superscript differ ($P < 0.05$).

[1] Phytase expressed as phytase units (FTU) per kilogram of diet.

The concentration of Ca in feces was reduced ($P < 0.05$) when microbial phytase was added to the diets containing the third hybrid of rye, barley, corn, or sorghum, and total daily output of Ca was also reduced ($P < 0.05$) when microbial phytase was added to the diets containing barley and corn. The ATTD of Ca was greater ($P < 0.05$) when microbial phytase was added to the diets containing the third hybrid of rye, barley, wheat, corn, and sorghum. Among diets without microbial phytase, the ATTD of Ca was greater ($P < 0.05$) in two of the hybrids of rye compared with sorghum, and the ATTD of Ca in one hybrid of rye was also greater ($P < 0.05$) than in corn. Among diets with microbial phytase, there was a greater ($P < 0.05$) ATTD of Ca in barley and the second hybrid of rye than in sorghum.

DISCUSSION

Concentrations of P and phytate-bound P in rye were in agreement with published data (NRC, 2012; Nørgaard et al., 2016; Stein et al., 2016); however, Rodehutscord et al. (2016) reported slightly greater concentrations of P in rye than observed in the present study. The analyzed concentration of Ca in rye and barley was lower than reported values (NRC, 2012; Nørgaard et al., 2016; Rodehutscord et al., 2016; Stein et al., 2016). The concentration of Ca in wheat was in agreement with published values (NRC, 2012; Rodehutscord et al., 2016), but the concentrations of P and phytate-bound P were greater than reported by NRC (2012). In contrast, Rodehutscord et al. (2016) and Stein et al. (2016) reported concentrations of P in wheat that were very close to what was observed in the present study. Concentrations of Ca, P, and phytate-bound P in corn and sorghum were also in agreement with published data (Almeida and Stein, 2012; NRC, 2012; Rodehutscord et al., 2016; Stein et al., 2016; Pan et al., 2017).

Limited data for the STTD of P in rye are available, and to our knowledge, no data for STTD of P in hybrid rye have been published. However, values for STTD of P in rye that were observed in this experiment are generally in agreement with STTD values observed in older cultivars of rye (NRC, 2012; Stein et al., 2016). The ATTD of P in rye with microbial phytase is around 60% (Nørgaard et al., 2016), but we are not aware of data for the STTD of P in rye with microbial phytase. The observed STTD of P in barley without microbial phytase was very close to the value reported by NRC (2012), whereas the observed values for wheat, corn, and sorghum without microbial phytase were less than previously reported. The observed STTD of P in corn with microbial phytase was, however, close to previously published data (Almeida and Stein, 2012).

Most P is stored as phytic acid in cereal grains, which makes it mostly unavailable for absorption and utilization by pigs (Simons et al., 1990). Addition of microbial phytase to diets increases P availability (Maga, 1982) and total tract digestibility of P in pigs (Almeida and Stein, 2010, 2012), which was also observed in the present experiment. The greater STTD of P without microbial phytase in the rye hybrids compared with wheat, corn, and sorghum may be due to the greater intrinsic phytase activity in rye. Processing of feed at high temperature, such as steam pelletting, decreases the intrinsic phytase activity in wheat (Jongbloed and Kemme, 1990). Therefore, if the intrinsic phytase activity in rye is the reason for the greater STTD of P compared with other grains without microbial phytase, it is likely the greater digestibility will only be observed in rye-based diets that are not heat treated. However, we are not aware of published data for effects of heat treatment of rye on the STTD of P.

Without microbial phytase, the STTD of P was greater in hybrid rye than in corn, and when microbial phytase was added to the diets, there was no difference in STTD of P among the rye hybrids and corn. Therefore, regardless of whether microbial phytase is added to the diets, the provision of digestible P from hybrid rye is slightly greater than from corn because hybrid rye contains greater concentrations of total P. Thus, these data indicate that if hybrid rye replaces corn in diets, less inorganic P will be needed.

Values for the ATTD of Ca calculated in the present experiment primarily represent the digestibility of Ca in limestone because the contribution of Ca from the cereal grains was very low. The present results support the observation by González-Vega et al. (2015) that the ATTD and STTD of Ca in calcium carbonate increases with the addition of microbial phytase. The ATTD of Ca in limestone observed in this experiment was in agreement with reported values obtained in corn-based diets (Stein et al., 2011; González-Vega et al., 2015). There is, however, limited data for the ATTD of Ca in limestone or calcium carbonate obtained in diets based on other cereal grains. The effect of microbial phytase on the digestibility of Ca observed in the present study supports the hypothesis that dietary Ca from limestone binds to phytate in the intestinal tract of pigs, as described by González-Vega et al. (2015). The intrinsic phytase in the rye is likely the reason there was no increase in ATTD of Ca when microbial phytase was added to the diets based on two of the hybrids of rye, whereas for the other cereal grains that have less or no intrinsic phytase,

addition of microbial phytase resulted in improved ATTD of Ca.

In summary, it is beneficial to include microbial phytase in swine diets that contain rye, barley, wheat, corn, or sorghum due to the increased STTD of P observed with microbial phytase supplementation. Without microbial phytase, the second hybrid of rye had greater STTD of P than wheat, corn, and sorghum, which supports the hypothesis that the digestibility of P is greater in hybrid rye than in other cereal grains because of the greater intrinsic phytase activity in rye. However, if microbial phytase was included in the diets, there were no differences in the STTD of P among the three hybrids of rye, and barley, and corn indicating that a certain level of phytase is needed to maximize STTD of P. Whether the phytase is of microbial origin or is intrinsic to the grain appears to be less important.

Conflict of interest statement. None declared.

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