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

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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[1]

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ABSTRACT: The objective of these studies was to determine if dietary enzymes increase the digestibility of nutrients bound by nonstarch polysaccharides, such as arabinoxylans, or phytate in wheat millrun. Effects of millrun inclusion rates (20 or 40%), xylanase (0 or 4,375 units/kg of feed), and phytase (0 or 500 phytase units/kg of feed) on nutrient digestibility and growth performance were investigated in a 2 × 2 × 2 factorial arrangement with a wheat control diet (0% millrun). Diets were formulated to contain 3.34 Mcal of DE/kg and 3.0 g of true ileal digestible Lys/Mcal of DE and contained 0.4% chromic oxide. Each of 18 cannulated pigs (36.2 ± 1.9 kg of BW) was fed 3 diets at 3× maintenance in successive 10-d periods for 6 observations per diet. Feces and ileal digesta were collected for 2 d. Ileal energy digestibility was reduced ($P < 0.01$) linearly by millrun and increased by xylanase ($P < 0.01$) and phytase ($P < 0.05$). Total tract energy digestibility was reduced linearly by millrun ($P < 0.01$) and increased by xylanase ($P < 0.01$). For 20% millrun, xylanase plus phytase improved DE content from 3.53 to 3.69 Mcal/kg of DM, a similar content to that of the wheat control diet (3.72 Mcal/kg of DM). Millrun linearly reduced ($P < 0.01$) ileal digestibility of Lys, Thr, Met, Ile, and Val. Xylanase improved ($P < 0.05$) ileal digestibility of Ile. Phytase improved ileal digestibility of Lys, Thr, Ile, and Val ($P < 0.05$). Millrun linearly reduced ($P < 0.05$) total tract P and Ca digestibility and retention. Phytase ($P < 0.01$) and xylanase ($P < 0.05$) improved total tract P digestibility, and phytase and xylanase tended to improve ($P < 0.10$) P retention. Phytase improved Ca digestibility ($P < 0.05$) and retention ($P < 0.01$). The 9 diets were also fed for 35 d to 8 individually housed pigs (36.2 ± 3.4 kg of BW) per diet. Millrun reduced ($P < 0.05$) ADFI, ADG, and final BW. Xylanase increased ($P < 0.05$) G:F; phytase reduced ($P < 0.05$) ADFI; and xylanase tended to reduce ($P = 0.07$) ADFI. In summary, millrun reduced energy, AA, P, and Ca digestibility and growth performance compared with the wheat control diet. Xylanase and phytase improved energy, AA, and P digestibility, indicating that nonstarch polysaccharides and phytate limit nutrient digestibility in wheat by-products. The improvement by xylanase of energy digestibility coincided with improved G:F but did not translate into improved ADG.

Key words: millrun, phytase, pig, wheat, xylanase

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INTRODUCTION

Dry milling of wheat removes much of the starch fraction in the grain to produce flour for human consumption and leaves wheat by-products as a residual (Holden and Zimmerman, 1991). Although wheat by-products generally have a greater content of nonstarch polysaccharides (**NSP**), CP, and minerals than the parent wheat (Slominski et al., 2004), nutrients such as AA are digested to a lesser extent than in the parent grain (Sauer et al., 1977). Swine do not digest feedstuffs with a high NSP content well (Barrera et al., 2004); therefore, the DE content of most grain by-products is low (NRC, 1998). In wheat by-products, P is partly bound as phytate P (Garcia-Estepa et al., 1999). Pigs

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do not produce endogenous phytase (Golovan et al., 2001), and are therefore inefficient in hydrolyzing phytate (Pointillart et al., 1984), resulting in a low P digestibility in grains and their by-products (NRC, 1998).

Replacing conventional energy-providing feedstuffs such as wheat in swine diets with low-cost by-products can be attractive economically. The low nutrient digestibility caused by NSP and phytate in wheat by-products indicates that xylanase and phytase supplementation may increase nutrient utilization. The current study tested the hypothesis that the nutrient digestibility of wheat millrun diets is lower than that of a wheat diet and can be improved by using xylanase and phytase, resulting in equivalent nutrient digestibility and growth performance.

The objectives of the digestibility and growth performance studies were as follows: 1) determine the linear and curvilinear effects of wheat millrun inclusion on the variables (a) ileal digestibility of energy, AA, P, and Ca, (b) total tract digestibility of energy, P, and Ca, and (c) growth performance; 2) determine the effects of xylanase and phytase supplementation in wheat millrun diets on these variables; and 3) compare the wheat control diet with the millrun diets supplemented with xylanase and phytase for these variables.

MATERIALS AND METHODS

Experimental Design and Diets

Effects of millrun inclusion rates (20 or 40%), xylanase (0 or 4,375 units/kg of feed), and phytase (0 or 500 phytase units/kg of feed) were tested in a 2 × 2 × 2 factorial arrangement in 8 wheat-based diets, together with a wheat control diet (0% millrun), for a total of 9 diets in a fractional factorial arrangement. The xylanase was endo-1, 4-β-xylanase (EC 3.2.1.8; Porzyme 9300; Danisco Animal Nutrition, Marlborough, UK), and the phytase was 6-phytase (EC 3.3.26; Phyzyme XP; Danisco Animal Nutrition). The wheat millrun used for this study was steam-pelleted (Dawn Foods, Saskatoon, Saskatchewan, Canada) to reduce bulk density and facilitate transport and was reground on a hammer mill across a 4-mm screen (New-Life Feeds, Saskatoon, Saskatchewan, Canada). The millrun contained the screenings, bran, and short fractions but not the middlings fraction after flour milling of hard red spring wheat. A DE content of 2,900 kcal/kg (as-fed) and true digestible Lys content of 0.41% was assumed for wheat millrun used in the current study for diet formulations based on values for its individual components such as bran and shorts (NRC, 1998). Fourteen other wheat by-product samples were collected in western Canada for comparison.

The wheat control diet and wheat millrun diets were formulated to an identical digestible nutrient content (3.34 Mcal of DE/kg; 3.0 g of true digestible Lys/Mcal of DE; Table 1) using canola oil and crystalline AA. In the diets, $NaHCO_3$ was included together with salt to maintain Na and ensure that Cl concentration was not elevated because of L-Lys·HCl inclusion rates. Diets were formulated to be at the requirement for digestible AA and marginally limiting in DE (by 60 kcal/kg) and were fortified to meet vitamin and mineral requirements (NRC, 1998). Xylanase and phytase were included at 167 and 100 g/metric ton of finished feed, respectively. Chromic oxide (0.4%) was added to diets used for the digestibility study as an indigestible marker.

Experimental Procedures

The animal protocols for the 2 studies were approved by the University of Saskatchewan Committee on Animal Care and Supply and followed established principles (CCAC, 1993). Two experiments were conducted at the Prairie Swine Centre Inc.

Exp. 1 (Digestibility Study). Eighteen crossbreed barrows (Camborough-22 × Line 65; PIC Canada Ltd., Airdrie, Alberta, Canada; initial BW, 36.2 ± 1.9 kg; initial age, 91 ± 7 d) were surgically fitted with a T-cannula at the distal ileum. Each pig was randomly fed 3 diets so that in each period, each diet was fed to 2 out of 18 pigs to provide 6 observations per pig, for a total of 54 observations. Pigs were housed in individual metabolism pens (1.5 × 1.5 m) that allowed freedom of movement. Pens had plastic-coated, expanded metal floors, polyvinyl chloride walls (0.9 m high) with plexiglass windows (0.3 × 0.3 m), 1 single-space dry feeder, and 1 bowl drinker. Urine collection trays (1.5 × 1.5 m) were installed underneath the pens during collection periods. Daily feed allowance was adjusted to 3 times maintenance (3 × 110 kcal of DE/kg of $BW^{0.75}$; NRC, 1998), which was fed in 2 equal meals at 0800 and 1600, resulting in an ADFI of 1.48, 1.68, and 1.94 kg/d during the first, second, and third periods, respectively. Diets were fed as a wet mash, with water added to the feed (approximately 1:1, wt/wt) immediately after adding feed to the feeder. Pigs had free access to water throughout the experiment. The three 10-d experimental periods consisted of a 6-d acclimation to the experimental diets, followed by a 2-d collection of feces and urine and a 2-d collection of ileal digesta. Each experimental period was followed by feeding a regular production diet without antibiotics for 4 d, for a total of 10 d between collections to avoid carryover effects.

Urine and feces were collected for a minimum of 2 times per day at 0800 and 1600. Urine drained into a 4-L bottle containing 20 mL of 12 *N* HCl to prevent volatilization of urinary N. Collected urine was weighed, and a 5% (by weight) subsample was filtered through cotton to remove solid particles. Digesta samples were collected for 2 d using bags containing diluted formic acid attached to the opened cannula barrel for 10 h. Feces were collected using plastic bags attached to the skin around the anus (Van Kleef et al., 1994). Collected digesta, feces, and subsampled urine were pooled by pig and frozen at –20°C. Before analyses,

Table 1. Ingredient and nutrient composition (as-fed basis) of the wheat control and 20 and 40% wheat millrun diets

Item	0% Wheat millrun (wheat control)	20% Wheat millrun[1]	40% Wheat millrun[1]
Ingredient, %			
Wheat	83.26	61.83	40.26
Wheat millrun	—	20.00	40.00
Soybean meal	12.50	12.50	12.50
Canola oil	—	1.80	3.60
Dicalcium phosphate	1.20	0.70	0.40
Limestone	0.85	1.00	1.10
L-Lys·HCl	0.49	0.47	0.45
Vitamin premix[2]	0.50	0.50	0.50
Mineral premix[3]	0.50	0.50	0.50
Sodium bicarbonate	0.29	0.29	0.29
Salt	0.20	0.20	0.20
L-Thr	0.15	0.14	0.13
DL-Met	0.06	0.07	0.07
Calculated nutrient content[4]			
DE, Mcal/kg	3.34	3.34	3.34
True digestible Lys,[5] g/Mcal of DE	3.0	3.0	3.0
Total P, %	0.60	0.60	0.60
Available P, %	0.41	0.31	0.25
Phytate P,[6] %	0.27	0.36	0.45
Ca, %	0.70	0.70	0.70
Analyzed mineral content, %			
Total P	0.64	0.64	0.62
Total Ca	0.74	0.71	0.68
Analyzed substrate content, %			
Nonstarch polysaccharide			
Insoluble	6.49	9.31	13.24
Soluble	4.97	3.09	2.69
Total	11.41	12.39	15.85
Arabinose			
Insoluble	1.41	1.94	2.47
Soluble	1.00	0.72	0.70
Total	2.38	2.66	3.16
Xylose			
Insoluble	2.15	3.28	4.86
Soluble	1.04	0.90	0.69
Total	3.17	4.18	5.56

[1]Xylanase was included at 167 g/1,000 kg of finished feed, and phytase was included at 100 g/1,000 kg of finished feed to create the enzyme-supplemented diets.

[2]Provided the following per kilogram of diet: vitamin A, 8,250 IU; vitamin D_3, 825 IU; vitamin E, 40 IU; niacin, 35 mg; D-pantothenic acid, 15 mg; riboflavin, 5 mg; menadione, 4 mg; folic acid, 2 mg; thiamine, 1 mg; D-biotin, 0.2 mg; and vitamin B_{12}, 0.025 mg.

[3]Provided the following per kilogram of diet: Zn, 100 mg as $ZnSO_4$; Fe, 80 mg as $FeSO_4$; Cu, 50 mg as $CuSO_4$; Mn, 25 mg as manganous sulfate; I, 0.5 mg as Ca iodate; and Se, 0.1 mg as Na_2SeO_3.

[4]Calculated content: 0.33% digestible Met, 0.56% digestible Thr, 0.26% digestible Cys, and 0.16% digestible Trp.

[5]Calculated content: 3.0 g of true digestible Lys/Mcal of DE (0.94% apparent digestible Lys) and an ideal pattern of apparent digestible AA compared with Lys [i.e., Thr, 60 and Met, 30 (NRC, 1998)].

[6]Calculated from analyzed phytate contents in wheat, millrun, and soybean meal (Haug and Lantzsch, 1983).

feces and digesta were thawed, homogenized, subsampled, and freeze-dried.

Exp. 2 (Performance Study). Seventy-two crossbreed pigs (36 barrows and 36 gilts; Camborough-22 × Line 65; PIC Canada Ltd.) with an initial BW of 36.2 ± 3.4 kg and initial age of 91 ± 7 d were used. Pigs were housed individually in 1 room and fed 1 experimental diet each for 35 d in 8 blocks to give 8 observations per diet. Within each block, barrows or gilts of equal BW were used. Pigs were selected within sex from a larger, single weaning group based on BW and assigned randomly within block and sex to 72 pens. The dimensions of the pens were 1.83 × 0.91 m. The flooring of the pen was fully slated concrete, and the siding was polyvinyl chloride planking. A single-space dry feeder was located at the front of the pen, and a nipple drinker was located at the back of the pen. The room was maintained within the thermoneutral zone for the pigs, with a 14-h light (0700 to 2100), 10-h dark cycle. The diets were provided ad libitum as a dry mash. Pigs had free access to water.

The feeders were checked daily to ensure that the feed was flowing freely.

Pigs were weighed at the beginning of the experimental period (d 0) and weekly thereafter (d 7, 14, 21, 28, and 35). On each weigh day, feed disappearance was determined, and the combined data were used to calculate ADG, ADFI, and G:F.

Chemical Analyses

Feed and freeze-dried feces and digesta were ground finely in a Retch mill (model ZMI, Brinkman Instruments, Rexdale, Ontario, Canada) over a 1-mm screen and analyzed for DM by drying at 135°C in an airflow-type oven for 2 h (method 930.15; AOAC, 1990). Chromic oxide content of feed, feces, and digesta was analyzed by spectrophotometry (model 80-2097-62, LKB-Ultraspec III, Pharmacia, Cambridge, UK) at 440 nm after ashing at 450°C overnight (Fenton and Fenton, 1979). The GE of feed, feces, and digesta was analyzed by an adiabatic bomb calorimeter (model 5003, Ika-Werke GMBH & Co. KG, Staufen, Germany); benzoic acid was used as a standard.

Feed, fecal, and digesta samples were analyzed for AA with precolumn derivation using phenylisothiocyanate (Guay et al., 2006). Norleucine was used as an internal marker and, following hydrolysis, the sample was dissolved in distilled water containing EDTA to chelate the metal ions. The Cys was determined as cysteic acid and Met as Met sulfone after preoxidation with performic acid and precolumn derivation using phenylisothiocyanate (Pierce Inc., Rockford, IL; Guay et al., 2006). Calcium and P in urine were determined using a Hitachi 912 analyzer (Zasoski and Burau, 1977). For Ca, a calorimetric end point determination method was used, and for P, an end point method with sample blanking method was used.

Phosphorus in feed, digesta, and fecal samples was analyzed by a spectrophotometer (model 80-2097-62, LKB-Ultraspec III, Pharmacia) at 470 nm after ashing at 600°C (method 965.17; AOAC, 1990). The wheat by-product samples were analyzed for ADF (method 973.18; AOAC, 1990), and NDF (Van Soest et al., 1991) was analyzed using a fiber analyzer (Ankom 200, Ankom Technology Corp., Fairport, NY). Diet samples were analyzed for soluble and insoluble NSP and constituent sugars by GLC (Englyst and Hudson, 1987).

Based on the results of the chemical analyses, apparent ileal digestibility of AA, total tract digestibility of Ca and P, ileal and total tract digestibility of GE and DM, and DE content were calculated using the Cr_2O_3 concentration of feed, digesta, and feces (Adeola, 2001). The ileal and total tract digestible Ca:P ratio was calculated. Daily Ca and P retention were calculated by determining daily Ca and P intake and deducting daily excretion of Ca and P in feces (calculated via the determined, apparent total tract digestibility) and urine.

Statistical Analyses

For Exp. 1, differences in digestibility of energy, AA, Ca, P, and DM among diets were analyzed as a completely randomized design using the GLM procedure (SAS Inst. Inc., Cary, NC). For Exp. 2, growth performance differences among diets were analyzed as a randomized complete block using the MIXED procedure of SAS.

For Exp. 1 and 2, diets containing millrun were analyzed as a $2 \times 2 \times 2$ factorial arrangement. The statistical model included the following effects: wheat millrun inclusion rate (20 and 40%), xylanase (with and without), and phytase (with and without) and all of their interaction terms. Linear and quadratic effects of millrun addition were determined using contrast statements for the 0, 20, and 40% control diets. In addition, the means of the wheat control diet and the 20 and 40% millrun diets with supplemental xylanase and phytase were separated by preplanned comparisons. Individual pig was considered as the experimental unit. Differences were considered significant if $P < 0.05$.

RESULTS

Nutrient Composition of Wheat By-Products

The collected wheat by-products samples varied widely in chemical composition (data not shown). The millrun sample used for the current study was greatest in ADF (overall range, 6.0 to 19.5% DM) and greater than average in NDF (41.7% DM; range, 19.6 to 42.4%). The high fiber content in this millrun sample increased the content of NSP, such as arabinose and xylose, in the 20 and 40% millrun diets (Table 1), thereby reflecting an increased content of arabinoxylans in diets containing millrun. Calculated phytate P content was also greater in diets containing millrun.

Energy and DM Digestibility

Ileal. Millrun inclusion linearly reduced ($P < 0.01$) energy digestibility from 77.5 to 62.0% and ileal DE content from 3.42 to 2.90 Mcal/kg of DM (Table 2). Xylanase and phytase independently improved ($P < 0.05$) energy digestibility and DE content in the millrun diets. Energy digestibility in xylanase and phytase-supplemented millrun diets did not approach the coefficient obtained with the wheat control diet. Xylanase and phytase together resulted in a similar DE content as the wheat control diet in the 20% millrun diets but not in the 40% millrun diets ($P < 0.05$). Millrun inclusion linearly reduced ($P < 0.01$) ileal DM digestibility from 79.4 to 63.4%. Xylanase and phytase independently improved ($P < 0.05$) ileal DM digestibility, but this improvement did not result in a coefficient that was equal to the wheat control diet ($P < 0.05$). Overall, xylanase and phytase did not interact to improve nutrient digestibility.

Table 2. Effect of wheat millrun inclusion rate and xylanase and phytase supplementation to wheat millrun diets on apparent ileal and total tract energy and DM digestibility and DE content of diets fed to grower pigs in Exp. 1[1]

	Millrun, %									*P*-value					
	0	20				40				Millrun[2]		Millrun diets[3]			
Item	WCON	CON	XYL	PHY	XYL + PHY	CON	XYL	PHY	XYL + PHY	Pooled SEM	LIN	QUAD	20 vs. 40%	XYL	PHY	XYL × PHY
Ileal digestibility																
Energy, %	77.5[a]	68.1	72.4	71.6	72.5[b]	62.0	68.1	67.4	66.6[c]	1.21	<0.01	0.29	<0.01	0.04	0.04	0.80
DE, Mcal/kg of DM	3.42[a]	3.10	3.29	3.26	3.32[ab]	2.90	3.20	3.14	3.13[b]	0.06	<0.01	0.40	<0.01	0.01	0.03	1.00
DM, %	79.4[a]	69.9	73.9	73.8	74.2[b]	63.4	69.2	68.7	67.9[c]	1.09	<0.01	0.27	<0.01	0.01	0.01	0.69
Total tract digestibility																
Energy, %	84.4[a]	77.6	79.8	78.9	80.7[b]	71.5	75.5	73.4	73.1[c]	0.55	<0.01	0.65	<0.01	<0.01	0.28	0.97
DE, Mcal/kg of DM	3.72[a]	3.53	3.63	3.59	3.69[a]	3.34	3.55	3.43	3.43[b]	0.03	<0.01	0.98	<0.01	<0.01	0.16	0.57
DM, %	86.7[a]	80.3	82.2	81.7	83.1[b]	74.2	77.9	76.1	75.9[c]	0.45	<0.01	0.76	<0.01	<0.01	0.09	0.95

[a–c]Means within the same row with the same superscript letters are not different ($P > 0.05$). Solely preplanned comparisons among the following 3 treatment means were made: wheat control and 0% millrun, xylanase plus phytase and 20% millrun, and xylanase plus phytase and 20% millrun. Superscripts are lacking if differences among these 3 means did not exist.

[1]Eighteen pigs (36.2 ± 1.9 kg) each fed 3 diets at 3× maintenance in subsequent 10-d periods for 6 observations per diet. Treatment means are reported as least squares means. WCON = wheat control; CON = control; XYL = xylanase; PHY = phytase; LIN = linear; QUAD = quadratic.

[2]Linear and quadratic responses were analyzed using control diets containing 0, 20, and 40% millrun.

[3]Source of variation and probability only among the 8 diets that contain millrun.

Total Tract. The inclusion of millrun linearly reduced total tract energy digestibility from 84.4 to 71.5% and total tract DE content from 3.72 to 3.34 Mcal/kg of DM ($P < 0.01$; Table 2). Xylanase, but not phytase, improved ($P < 0.01$) energy digestibility and the DE content in the millrun diets. For 20% millrun, xylanase plus phytase improved DE content from 3.53 to 3.69 Mcal/kg of DM, a similar content as the wheat control diet (3.72 Mcal/kg of DM). Xylanase and phytase did not interact to improve energy digestibility. Millrun inclusion reduced ($P < 0.01$) DM digestibility from 86.7 to 74.2%. Xylanase improved ($P < 0.01$) and phytase tended to improve ($P = 0.07$) DM digestibility in the millrun diets but not to a coefficient equal to that of the wheat control diet ($P < 0.05$).

Ileal AA Digestibility

Millrun inclusion linearly reduced apparent digestibility of all AA (Table 3). Specifically, digestibility of Lys, Thr, Met, Cys, and Ile decreased by 7.8, 10.4, 7.1, 7.7, and 9.1% units, respectively ($P < 0.01$). Within millrun diets, xylanase improved ($P < 0.05$) digestibility of Ile and Phe and tended to improve ($P < 0.10$) digestibility of Leu, Thr, and Tyr. Phytase supplementation improved ($P < 0.05$) ileal digestibility of Arg, His, Ile, Leu, Lys, Thr, Tyr, and Val and tended to improve ($P = 0.06$) Phe digestibility. Xylanase and phytase interacted to improve ($P < 0.05$) ileal digestibility of His.

P and Ca Digestibility

Millrun addition linearly reduced ($P < 0.05$) ileal P digestibility from 53.8 to 34.8% and total tract P digestibility from 59.5 to 42.9% (Table 4). Xylanase and phytase supplementation tended to improve ($P < 0.10$) ileal P digestibility. Xylanase and phytase interacted to improve ($P < 0.01$) total tract P digestibility ($P = 0.05$ and $P < 0.01$, respectively) to coefficients similar statistically to that of the wheat control diet. For 20% millrun, xylanase plus phytase improved total tract P digestibility from 45.3 to 60.2%, a similar content as the wheat control diet (59.5%).

The inclusion of millrun reduced ileal and total tract digestible P content curvilinearly (linear, $P < 0.01$; quadratic, $P < 0.05$; Table 4). The minimum content seems to be 0.24 and 0.29 g/kg of DM for ileal and total tract digestible P, respectively. Xylanase ($P < 0.05$), but not phytase, improved ileal digestible P. Xylanase and phytase acted synergistically to improve ($P < 0.01$) total tract digestible P, resulting in a similar digestible P content as the wheat control diet in the enzyme-supplemented 20% millrun diet but not the 40% millrun diet ($P < 0.05$).

The addition of millrun linearly reduced ($P < 0.05$) ileal Ca digestibility from 62.5 to 45.1% and total tract Ca digestibility from 61.6 to 45.2% (Table 4). Xylanase or phytase did not affect ileal Ca digestibility. Phytase, but not xylanase, improved ($P = 0.05$) total tract Ca

Table 3. Effect of wheat millrun inclusion rate and xylanase and phytase supplementation to wheat millrun diets on apparent ileal AA digestibility of diets fed to grower pigs in Exp. 1[1]

	Millrun, %									*P*-value					
	0	20				40					Millrun[2]		Millrun diets[3]		
Item	WCON	CON	XYL	PHY	XYL + PHY	CON	XYL	PHY	XYL + PHY	Pooled SEM	LIN	QUAD	20 vs. 40%	XYL	PHY	XYL × PHY
Ileal AA digestibility, %																
Ala	73.9	67.9	66.3	66.7	69.5	58.1	63.7	67.9	70.6	2.64	<0.01	0.56	0.18	0.22	0.02	0.10
Arg	85.5	83.3	83.9	85.2	85.4	82.4	85.8	85.9	84.7	0.96	0.02	0.60	0.71	0.25	0.03	0.89
Asp	83.3[a]	77.6	80.3	79.6	78.3[ab]	74.2	78.3	78.6	75.2[b]	1.65	<0.01	0.57	0.05	0.67	0.79	0.09
Cys	80.5[a]	76.1	75.7	76.1	74.4[b]	72.8	74.6	72.9	74.9[b]	1.42	<0.01	<0.01	0.79	0.07	0.21	0.88
Glu	91.0[a]	88.5	89.9	89.6	90.5[ab]	85.6	88.7	87.9	87.6[b]	0.68	<0.01	0.82	<0.01	0.01	0.14	0.95
Gly	74.2	69.2	69.2	70.7	73.3	64.6	68.6	68.7	68.9	1.49	<0.01	0.92	<0.01	0.12	0.02	0.17
His	82.5	77.6	79.6	78.7	82.4	76.9	78.7	79.6	79.8	0.87	<0.01	0.05	0.21	<0.01	<0.01	0.01
Ile	83.8[a]	79.2	79.7	79.2	81.2[ab]	74.7	78.6	79.4	78.6[b]	0.97	<0.01	0.99	<0.01	0.05	0.03	0.43
Leu	84.6[a]	80.1	81.1	80.9	82.0[ab]	76.1	79.7	80.9	79.8[b]	0.93	<0.01	0.85	<0.01	0.09	0.01	0.73
Lys	86.4	82.0	82.9	82.7	83.5	78.6	82.6	83.7	82.4	1.03	<0.01	0.72	0.19	0.13	0.04	0.73
Met	86.6[a]	81.5	79.9	84.7	80.8[ab]	79.5	79.9	81.5	79.2[b]	1.49	<0.01	0.42	0.11	0.09	0.23	0.24
Phe	86.8[a]	81.2	83.4	83.4	83.2[b]	77.5	83.1	81.8	80.8[b]	0.74	<0.01	0.35	<0.01	<0.01	0.06	0.16
Pro	89.1[a]	84.9	85.7	85.8	86.9[ab]	80.9	83.9	84.9	84.5[b]	0.79	<0.01	0.87	<0.01	0.05	<0.01	0.35
Ser	82.5	78.9	79.2	79.2	81.2	75.6	77.3	78.7	78.1	1.14	<0.01	0.92	<0.01	0.31	0.06	0.30
Thr	80.4[a]	74.9	75.1	76.2	77.9[ab]	70.0	73.9	75.4	75.3[b]	1.21	<0.01	0.82	<0.01	0.09	<0.01	0.19
Tyr	85.5[a]	78.5	80.4	79.8	81.7[b]	75.0	77.9	79.6	78.5[b]	0.99	<0.01	0.16	<0.01	0.06	<0.01	0.41
Val	82.5	76.1	77.1	76.9	78.7	72.1	74.3	76.9	76.2	1.24	<0.01	0.43	0.01	0.23	0.01	0.31

[a,b]Means within the same row with the same superscript letters are not different ($P > 0.05$). Solely preplanned comparisons among the following 3 treatment means were made: wheat control and 0% millrun, xylanase plus phytase and 20% millrun, and xylanase plus phytase and 20% millrun. Superscripts are lacking if differences among these 3 means did not exist.

[1]Treatment means are reported as least squares means. WCON = wheat control; CON = control; XYL = xylanase; PHY = phytase; LIN = linear; QUAD = quadratic.

[2]Linear and quadratic responses were analyzed using control diets containing 0, 20, and 40% millrun.

[3]Source of variation and probability only among the 8 diets that contain millrun.

digestibility. The addition of millrun linearly reduced ($P < 0.01$) ileal digestible Ca from 0.53 to 0.34 g/d and total tract digestible Ca from 0.52 to 0.34 g/d. Xylanase and phytase acted individually ($P < 0.05$) and also interacted to improve ($P < 0.01$) total tract digestible Ca content; however, the combined effects did not result in contents equal to that of the wheat control diet.

The addition of millrun increased the ileal digestible Ca:P ratio (quadratic, $P < 0.05$; Table 4); the minimum value seems to be 1.12. Xylanase, but not phytase, reduced the ileal Ca:P ratio ($P < 0.01$) to a ratio similar to the wheat control diet. The total tract digestible Ca:P ratio was not affected by millrun, xylanase, or phytase.

P and Ca Retention

Daily intake of P was not affected by millrun inclusion or enzymes and was similar among diets (Table 5). Millrun linearly increased ($P < 0.05$) fecal P excretion from 4.9 to 6.6 g/d. Neither millrun nor enzyme affected urinary P excretion. Phytase, but not xylanase, reduced ($P < 0.01$) P excretion in millrun diet, and an interaction of phytase with xylanase reduced ($P < 0.01$) fecal P excretion further than solely with phytase. Millrun linearly reduced ($P = 0.01$) P retention from 7.3 to 4.9 g/d. Xylanase and phytase tended to improve P retention ($P < 0.10$). Phytase and xylanase interacted ($P < 0.05$) so that their combined effect resulted in P retention similar to that of the wheat control diet. For 20% millrun, xylanase plus phytase improved P retention from 4.9 to 6.5 g/d, a similar retention as the wheat control diet (7.3 g/d).

Millrun inclusion did not affect daily Ca intake (Table 5). Millrun tended to increase ($P = 0.05$) fecal Ca excretion. Phytase, but not xylanase, tended to reduce ($P = 0.09$) fecal Ca excretion. Millrun inclusion, phytase, and xylanase did not affect urinary Ca excretion. Millrun linearly reduced ($P < 0.01$) Ca retention from 7.8 to 5.9 g/d. Xylanase, but not phytase, improved ($P < 0.01$) Ca retention in the millrun diets.

Growth Performance

Millrun linearly reduced ($P < 0.01$) BW at all stages of the experiment (Table 6). On d 35, pigs fed the 40% millrun diet were 7.9 kg lighter than pigs fed the wheat control diet ($P < 0.01$). Xylanase or phytase did not affect BW.

Millrun inclusion linearly reduced ($P < 0.05$) ADFI from 1.9 to 1.6 kg/d for d 0 to 7 and from 2.3 to 1.9 kg/d for d 8 to 14 (Table 6). Xylanase reduced ($P < 0.01$) ADFI from 2.7 to 2.5 kg/d for d 15 to 21 and tended to reduce ($P = 0.07$) ADFI from 2.5 to 2.4 kg/d for d 0 to 35. Phytase reduced ($P = 0.01$) ADFI from 2.9 to 2.5 kg/d for d 22 to 28 and from 3.3 to 2.9 kg/d for d 29 to 35 and reduced ($P < 0.05$) ADFI from 2.6 to 2.4 kg/d for d 0 to 35. Xylanase and phytase did not interact to affect ADFI.

Table 4. Effect of wheat millrun inclusion rate and xylanase and phytase supplementation to wheat millrun diets on apparent ileal and total tract P and Ca digestibility and digestible P and Ca contents of diets fed to grower pigs in Exp. 1[1]

	Millrun, %										*P*-value					
	0	20				40					Millrun[2]		Millrun diets[3]			
Item	WCON	CON	XYL	PHY	XYL + PHY	CON	XYL	PHY	XYL + PHY	Pooled SEM	LIN	QUAD	20 vs. 40%	XYL	PHY	XYL × PHY
Ileal digestibility, %																
P	53.8	40.5	46.0	42.7	47.9	34.8	37.4	40.2	43.7	3.09	<0.01	0.32	0.02	0.06	0.08	0.12
Ca	62.5	53.9	52.2	54.6	47.9	45.1	40.9	46.1	50.6	4.75	0.01	0.99	0.04	0.66	0.71	0.93
Ileal digestible minerals, g/kg of DM																
P	0.38[a]	0.26	0.31	0.26	0.31[b]	0.24	0.25	0.26	0.29[b]	0.02	<0.01	0.04	0.06	0.02	0.33	0.12
Ca	0.53[a]	0.42	0.38	0.43	0.33[b]	0.34	0.27	0.32	0.33[b]	0.03	<0.01	0.89	<0.01	0.03	0.92	0.49
Ca:P	1.35	1.65	1.23	1.67	1.05	1.42	1.12	1.21	1.15	0.08	0.58	0.02	<0.01	<0.01	0.16	<0.01
Total tract digestibility, %																
P	59.5	45.3	47.5	51.9	60.2	42.9	44.4	45.9	53.5	3.45	0.01	0.18	0.07	0.05	<0.01	<0.01
Ca	61.6[a]	53.6	54.7	59.3	57.3[ab]	45.2	45.2	49.7	48.1[b]	2.81	<0.01	0.95	<0.01	0.74	0.05	0.85
Total tract digestible minerals, g/kg of DM																
P	0.43[a]	0.29	0.31	0.32	0.39[ab]	0.29	0.29	0.29	0.35[b]	0.02	<0.01	0.02	0.16	0.02	0.02	<0.01
Ca	0.52[a]	0.43	0.38	0.47	0.37[b]	0.34	0.30	0.35	0.31[b]	0.02	<0.01	0.02	0.16	0.02	0.02	<0.01
Ca:P	1.22	1.45	1.21	1.49	1.03	1.19	1.03	2.17	1.0	0.38	0.96	0.59	0.92	0.05	0.52	0.12

[a,b]Means within the same row with the same superscript letters are not different ($P > 0.05$). Solely preplanned comparisons among the following 3 treatment means were made: wheat control and 0% millrun, xylanase plus phytase and 20% millrun, and xylanase plus phytase and 20% millrun. Superscripts are lacking if differences among these 3 means did not exist.

[1]Treatment means are reported as least squares means. WCON = wheat control; CON = control; XYL = xylanase; PHY = phytase; LIN = linear; QUAD = quadratic.

[2]Linear and quadratic responses were analyzed using control diets containing 0, 20, and 40% millrun.

[3]Source of variation and probability only among the 8 diets that contain millrun.

Table 5. Effect of wheat millrun inclusion rate and xylanase and phytase supplementation to wheat millrun diets on P and Ca intake, excretion, and retention of diets fed to grower pigs in Exp. 1[1]

	Millrun, %										*P*-value					
	0	20				40					Millrun[2]		Millrun diets[3]			
Item	WCON	CON	XYL	PHY	XYL + PHY	CON	XYL	PHY	XYL + PHY	Pooled SEM	LIN	QUAD	20 vs. 40%	XYL	PHY	XYL × PHY
P, g/d																
Intake	12.4	11.0	11.4	10.5	11.1	11.6	11.5	11.0	11.0	0.58	0.37	0.19	0.46	0.62	0.25	0.90
Urine	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.03	0.44	0.72	0.23	0.26	0.52	0.99
Feces	4.9	6.0	5.9	5.0	4.4	6.6	6.4	6.1	5.2	0.53	0.04	0.69	0.06	0.24	<0.01	0.03
Excretion	5.1	6.1	6.1	5.1	4.5	6.7	6.6	6.2	5.3	0.54	0.04	0.71	0.06	0.27	<0.01	0.03
Retention	7.3	4.9	5.3	5.4	6.5	4.9	4.9	4.8	5.7	0.48	0.01	0.05	0.21	0.07	0.09	0.02
Ca, g/d																
Intake	13.1[a]	12.3	10.8	12.5	10.8[ab]	11.7	10.5	10.8	10.1[b]	0.58	0.11	0.91	0.06	<0.01	0.52	0.16
Urine	0.2	0.2	0.2	0.2	0.2	0.3	0.3	0.2	0.2	0.06	0.41	0.75	0.24	0.28	0.48	0.98
Feces	5.0	5.7	4.9	5.1	4.6	6.4	5.7	5.5	5.3	0.46	0.05	0.96	0.06	0.11	0.09	0.39
Excretion	5.2	5.9	5.1	5.3	4.9	6.6	6.1	5.7	5.5	0.49	0.05	0.99	0.06	0.17	0.09	0.42
Retention	7.8[a]	6.5	5.7	7.2	5.9[b]	5.9	4.4	5.1	4.6[b]	0.35	<0.01	0.85	<0.01	<0.01	0.19	0.24

[a,b]Means within the same row with the same superscript letters are not different ($P > 0.05$). Solely preplanned comparisons among the following 3 treatment means were made: wheat control and 0% millrun, xylanase plus phytase and 20% millrun, and xylanase plus phytase and 20% millrun. Superscripts are lacking if differences among these 3 means did not exist.

[1]Treatment means are reported as least squares means. WCON = wheat control; CON = control; XYL = xylanase; PHY = phytase; LIN = linear; QUAD = quadratic.

[2]Linear and quadratic responses were analyzed using control diets containing 0, 20, and 40% millrun.

[3]Source of variation and probability only among the 8 diets that contain millrun.

Millrun linearly reduced ($P < 0.01$) ADG from 0.96 to 0.77 kg/d for d 0 to 7, from 1.23 to 1.02 kg/d for d 15 to 21 ($P < 0.01$), and tended to reduce ADG from 1.02 to 0.95 kg/d for d 0 to 35 ($P < 0.06$; Table 6). For d 0 to 35, xylanase or phytase did not affect ADG.

Millrun linearly reduced ($P < 0.01$) G:F from 0.46 to 0.37 for d 15 to 21 (Table 6), and xylanase tended to increase ($P = 0.05$) G:F. For d 0 to 35, millrun linearly reduced ($P = 0.05$) G:F, and xylanase improved ($P < 0.05$) G:F from 0.38 to 0.40. Phytase did not affect G:F.

DISCUSSION

In the current study, the inclusion of wheat millrun in diets for growing pigs reduced DE content; digestibility of energy, AA, Ca and P; and growth performance. Individually or combined supplementation of xylanase and phytase in millrun diets improved DE content and nutrient digestibility. Xylanase supplementation improved G:F, but neither xylanase nor phytase improved ADG.

Millrun Addition

Wheat by-products of dry milling for flour production include the following fractions: bran, shorts, screenings, and middlings (AAFCO, 1988). In western Canada, wheat millrun is produced by combining all or most of these fractions. The selected millrun sample contained the shorts, bran, and screenings fractions. The reduced DE content of millrun diets indicates that the actual DE content of millrun was lower than the assumed content of 2,900 kcal/kg (as-fed). The energy values of wheat by-products require further definition.

The addition of wheat millrun to a wheat-based diet reduced energy, AA, and DM digestibility, likely due to an increased content of NSP, which pigs do not digest well (Barrera et al., 2004). The increased NSP content interferes with digestibility of other macronutrients, thereby reducing energy digestibility (Bell et al., 1983). The NSP in wheat and thus wheat by-products are mostly arabinoxylans and cellulose (Zijlstra et al., 1999). These NSP encapsulate nutrients and can thereby act as a physical barrier to effective nutrient hydrolysis and absorption.

Wheat millrun inclusion reduced P and Ca digestibility and retention. The reduction is likely due to a combined effect of increased phytate content, antinutritional effects of NSP (Barrera et al., 2004), and the limited ability of pigs to digest phytate P (Selle et al., 2000). Dietary Ca will be bound to phytic acid to form phytate, which renders the Ca unavailable to the pig.

Millrun inclusion reduced G:F, ADG, and final BW in the current study. Millrun inclusion did not affect ADFI, but the reduced DE content indicates that millrun inclusion reduced DE intake. The increase in NSP content in millrun diets might have prevented the expected increase in ADFI that may have compensated for the reduced DE content (NRC, 1998). Together with the simultaneously reduced G:F, the reduced ADG with millrun inclusion can thereby be explained.

Xylanase Supplementation

Xylanase supplementation of the millrun diets improved energy and DM digestibility and DE content in the current study. By-products of cereal grains have a high content of NSP (Slominski et al., 2004). Pigs do

Table 6. Effect of wheat millrun inclusion rate and xylanase and phytase supplementation to wheat millrun diets on performance of grower pigs over time in Exp. 2[1]

	Millrun, %										*P*-value						
	0	20				40					Millrun[2]		Millrun diets[3]				
Item	WCON	CON	XYL	PHY	XYL + PHY	CON	XYL	PHY	XYL + PHY	Pooled SEM	LIN	QUAD	20 vs. 40%	XYL	PHY	XYL × PHY
BW, kg																	
d 7	42.3[a]	41.7	41.9	41.4	41.7[ab]	40.9	41.1	40.9	40.8[b]	0.36	<0.01	0.77	<0.01	0.50	0.40	0.80
d 14	53.5[a]	50.0	48.2	47.3	47.7[b]	47.3	46.6	47.3	46.9[b]	0.83	<0.01	0.02	0.19	0.85	0.75	0.98
d 21	61.9[a]	55.7	55.1	54.7	55.0[b]	54.5	53.7	54.6	53.9[b]	0.98	<0.01	0.04	0.08	0.80	0.51	0.70
d 28	68.4[a]	62.4	62.5	60.5	61.3[b]	60.8	60.1	60.8	60.5[b]	1.21	<0.01	0.14	0.19	0.96	0.43	0.92
d 35	76.5[a]	70.4	70.1	67.4	68.7[b]	68.6	67.5	68.4	67.7[b]	1.45	<0.01	0.23	0.29	0.86	0.30	0.94
ADFI, kg/d																
d 0 to 7	1.92	1.99	1.74	1.82	1.82	1.63	1.76	1.71	1.69	0.07	<0.01	0.03	0.04	0.46	0.53	0.84
d 8 to 14	2.31[a]	2.25	2.06	2.06	1.98[b]	1.92	1.96	2.31	2.04[ab]	0.12	0.04	0.40	0.77	0.15	0.59	0.40
d 15 to 21	2.72[a]	2.64	2.57	2.57	2.38[b]	2.76	2.44	2.57	2.41[b]	0.10	0.77	0.39	0.98	0.01	0.08	0.09
d 22 to 28	2.84[a]	2.84	2.75	2.49	2.60[b]	2.92	2.69	2.49	2.49[b]	0.14	0.68	0.79	0.84	0.57	0.01	0.59
d 29 to 35	3.21[a]	3.20	3.07	2.84	2.94[ab]	3.33	3.12	2.95	2.78[b]	0.15	0.60	0.71	0.76	0.34	0.01	0.31
d 0 to 35	2.53	2.61	2.43	2.34	2.34	2.54	2.40	2.43	2.28	0.09	0.93	0.49	0.76	0.07	0.02	0.26
ADG, kg/ d																
d 0 to 7	0.96[a]	0.88	0.92	0.85	0.88[ab]	0.77	0.81	0.77	0.76[b]	0.07	<0.01	0.77	<0.01	0.45	0.43	0.77
d 8 to 14	0.90	0.89	0.90	0.85	0.86	0.90	0.77	0.91	0.87	0.05	0.94	0.84	0.78	0.31	0.85	0.87
d 15 to 21	1.23[a]	1.09	1.14	1.07	1.04[b]	1.02	1.01	1.03	0.99[b]	0.06	<0.01	0.65	0.08	0.90	0.38	0.37
d 22 to 28	0.97	0.95	0.91	0.84	0.89	0.89	0.91	0.88	0.94	0.08	0.37	0.86	0.88	0.58	0.45	0.53
d 29 to 35	1.19[a]	1.13	1.08	0.99	1.07[ab]	1.10	1.06	1.08	1.03[b]	0.06	0.35	0.88	0.98	0.71	0.24	1.00
d 0 to 35	1.02[a]	0.99	0.99	0.91	0.95[ab]	0.95	0.92	0.94	0.92[b]	0.03	0.06	0.73	0.14	0.79	0.14	0.91
G:F																
d 0 to 7	0.49	0.45	0.53	0.47	0.49	0.46	0.46	0.44	0.46	0.02	0.26	0.20	0.10	0.07	0.53	0.95
d 8 to 14	0.39	0.39	0.43	0.41	0.44	0.42	0.39	0.41	0.42	0.04	0.33	0.56	0.71	0.41	0.48	0.30
d 15 to 21	0.46	0.41	0.45	0.41	0.44	0.37	0.42	0.40	0.42	0.02	<0.01	0.87	0.07	0.05	0.64	0.64
d 22 to 28	0.34	0.33	0.33	0.34	0.35	0.31	0.35	0.36	0.37	0.02	0.34	0.77	0.48	0.30	0.14	0.30
d 29 to 35	0.37	0.36	0.35	0.35	0.36	0.34	0.34	0.36	0.37	0.02	0.19	0.77	0.86	0.72	0.28	0.33
d 0 to 35	0.41	0.39	0.42	0.39	0.41	0.38	0.39	0.39	0.41	0.01	0.05	0.60	0.24	0.03	0.29	0.24

[a,b]Means within the same row with the same superscript letters are not different ($P > 0.05$). Solely preplanned comparisons among the following 3 treatment means were made: wheat control and 0% millrun, xylanase plus phytase and 20% millrun, and xylanase plus phytase and 20% millrun. Superscripts are lacking if differences among these 3 means did not exist.

[1]Treatment means are reported as least squares means. WCON = wheat control; CON = control; XYL = xylanase; PHY = phytase; LIN = linear; QUAD = quadratic.

[2]Linear and quadratic responses were analyzed using control diets containing 0, 20, and 40% millrun.

[3]Source of variation and probability only among the 8 diets that contain millrun.

not produce the endogenous enzymes that are required to digest NSP; therefore, supplementation of NSP-degrading enzymes in high-NSP diets is one approach to reduce detrimental effects of NSP and improve the nutritional value for young pigs (Li et al., 1996). In diets containing wheat bran, NSP-degrading enzymes have been found to increase soluble saccharides in the stomach and small intestine and increase VFA in the ileum (Van der Meulen et al., 2001), indicating that NSP-degrading enzymes move NSP digestion partially from the large intestine to the small intestine. The NSP-degrading enzymes thus can improve energy utilization of high-NSP diets in young pigs (Graham et al., 1986).

Xylanase improved apparent AA digestibility, similar to improved AA digestibility in wheat-based diets fed to grower pigs (Barrera et al., 2004), indicating that wheat NSP hamper AA digestibility. The arabinoxylans enclose AA in the grain, thus directly interfering with AA digestion and absorption in the small intestine, or enhance secretion of endogenous AA.

Xylanase supplementation of the millrun diets improved ileal and total tract P digestibility. In mature cereal grains, a large portion of the P is present as phytate-bound P (Ravindran et al., 1994). Bran and kernel layers of wheat are major storage sites of phytate and P (Maga, 1982). These sites contain arabinoxylans, which are a major substrate for xylanase. The improved P digestibility might thus be an indirect benefit of xylanase, because P, either bound or not bound to phytase, would be better exposed to digestive enzymes or supplemental phytase.

The NSP-degrading enzymes have had inconsistent effects on growth performance in swine (Bedford and Schulze, 1998). For example, Zijlstra et al. (2004) found that supplementation of a NSP-degrading enzyme to a wheat and canola meal-based diet improved ADG as a result of improved ADFI. Improved ADG has also been attributed to improved G:F (Bedford et al., 1992; Van Lunen and Schulze, 1996). In contrast, xylanase supplementation of millrun diets has tended to reduce ADFI,

improve overall G:F, and did not affect ADG in the current study. Xylanase supplementation was thereby unable to correct the lower final BW observed with millrun diets compared with the wheat control diet, because the improved G:F was negated by a reduced ADFI.

Nutrient content and imbalances in feed can affect voluntary feed intake in pigs (Nyachoti et al., 2004). Energy content affects feed intake in most scenarios (NRC, 1998). Dietary CP and AA balance also influence feed intake (Henry et al., 1992). Apart from nutrients, physical capacity might also limit feed intake of pigs. In the current study, the millrun diets had a lower DE content than the wheat control diet and were bulkier. The physical feed intake capacity might explain the reduced ADFI during the first 2 wk of the current study. The release of nutrients with xylanase supplementation might reduce feed intake because of 2 reasons: 1) extra released nutrients might trigger a feedback mechanism to reduce feed intake as a result of a glucostatic or aminostatic response or 2) a nutrient imbalance within the gastrointestinal tract of the pig. Both scenarios would combine improved nutrient digestibility with a lowered ADFI, as was observed with xylanase supplementation.

Phytase Supplementation

Phytic acid is the major P storage compound of most seeds and cereal grains. In wheat, phytic acid is mostly contained in the bran, which contains 5% phytic acid (Garcia-Estepa et al., 1999). Wheat contains 0.32% phytate, with approximately 87% of it contained in the aleurone layer, 13% in the germ, 2% in the endosperm, and 0% in the hull (O'Dell et al., 1972). Phytic acid can form complexes with multivalent cations such as Ca, Mg, Zn, and Fe, starch, free AA, and proteins (Selle et al., 2000) and thus exists in many forms. Most of the P in plant-based feedstuffs is present as phytate P (Liao et al., 2005). Another form is phytin, which is the Ca and Mg salt of phytic acid (Oatway et al., 2001). Phytate mineral complexes are generally insoluble at physiological pH (Ravindran et al., 1994), and bound minerals are thus unavailable to swine.

Phytase improved ileal and total tract DE contents and DM digestibility. Adding phytase to feeds containing phytate can catalyze the removal of the orthophosphate group from phytate (Maga, 1982), thereby releasing the bound nutrients and improving nutrient digestibility. Phytic acid binds the main energy macronutrient for swine, starch, through H bonding (Oatway et al., 2001). Pigs have a limited ability to digest phytate P, because endogenous phytase necessary for hydrolysis of phytate is lacking (Golovan et al., 2001). Consequently, increasing the inclusion rate of wheat by-products in diets for swine will increase dietary phytic acid content and subsequently reduce energy, AA, and P digestibility, as occurred in the current study.

Effects of phytase on energy digestibility of swine diets are rarely studied. Supplementing phytase to rice bran-based diets either low or high in phytate has been shown to not affect apparent ileal digestibility of GE in grower pigs (Liao et al., 2005). Dietary Ca and available P content of the experimental diets might affect phytase efficacy. The combination of a reduced Ca and P content and phytase supplementation increased nutrient and energy digestibility in diets for pigs (Johnston et al., 2004). The improved DE content with phytase in the current study indicates that complexes between phytic acid and macronutrients in the millrun are significant and that energy is less available without phytase supplementation.

The wheat millrun in the current study might have been low in intrinsic phytase activity. In cereals, intrinsic phytases are located primarily in the aleurone layers (Oatway et al., 2001), the outermost endosperm tissue of wheat that contains protein bodies that store phytase. Logically, supplementation of exogenous phytase to the millrun-based diets should have had limited effect on nutrient digestibility, because millrun should have significant intrinsic phytase activity. However, the millrun was steam-pelleted, which likely reduced or eliminated intrinsic phytase activity, because wheat phytase is heat-labile, thereby explaining the positive response in nutrient digestibility to exogenous phytase.

The efficacy of phytase in improving the AA availability is still a matter of debate. Phytase supplementation has been shown to improve apparent AA digestibility in some studies in swine (Mroz et al., 1994; Liao et al., 2005), whereas other studies have reported a lack of improvements in protein or AA digestibility (Bruce and Sundstol, 1995; Traylor et al., 2001). The interaction between phytase and AA digestion might thus be multifaceted. In the current study, phytase supplementation improved apparent ileal digestibility of Lys, Thr, Val, Leu, and Ile. Phytate thus clearly binds AA in wheat millrun (Selle et al., 2000). Four possible complexes exist in pigs and poultry between phytin and protein that lower protein digestion (Selle et al., 2000; Kies et al., 2001). These include the following: 1) phytin-protein complexes in feedstuffs, 2) complexes between phytin and proteolytic enzymes, 3) de novo complexes between phytin and proteins during intestinal transit, and 4) de novo complexes between phytin and free AA during intestinal transit in the animal. Variations in these complexes may contribute to the conflicting results in the literature.

The effects of phytase on P digestibility or availability in plant-based feedstuffs have been well documented. In young pigs, phytase has been shown to increase P availability (Yi et al., 1996), and an *Escherichia coli*-derived phytase has been shown to improve Ca and P digestibility and retention (Adeola et al., 2004). In the current study, phytase supplementation to the millrun diets improved apparent P and Ca digestibility, indicating that both P and Ca are being liberated from phytate P and phytin.

Phytase supplementation reduced ADFI and did not affect ADG and G:F in the current study. Pigs fed the millrun diets had a lower final BW than that of pigs fed the wheat control diet, and phytase did not improve final BW of pigs fed millrun diets. Furthermore, supplemental phytase might have released nutrients, resulting in a dietary nutrient imbalance and reduced ADFI. The lack of increased ADG might be expected, because the diets were not limiting in P, and excess dietary P does not increase ADG (Ekpe et al., 2002). In contrast, phytase supplementation to diets limiting in P improved ADG and G:F in young pigs (Adeola et al., 2004).

Xylanase and Phytase Interaction

Xylanase and phytase interacted positively on P digestibility in the current study, indicating a synergy between the 2 enzymes in hydrolyzing P. Specifically, apparent total tract digestibility was improved 1.9 percentage units by xylanase, 4.8 percentage units by phytase, and 12.8 percentage units by the combination of xylanase and phytase, as opposed to the cumulative 6.7 percentage units. Enzyme synergy exists if the effect of the 2 enzymes combined is greater than the cumulative effect of each single enzyme. This synergy might exist because supplemental xylanase disrupts the cell wall matrix and hydrolyzes otherwise unavailable carbohydrates, while at the same time allowing the supplemental phytase to gain access to phytate-bound nutrients like P, proteins, and starch (Oryschak et al., 2002). The synergy might also be caused by changes in digesta passage rate, thereby allowing a prolonged contact time of the phytase with its substrate at the optimum pH.

In conclusion, wheat millrun has the potential to partially replace energy-yielding feedstuffs for grower-finisher pigs. The inclusion of wheat millrun into swine diets, however, reduced digestibility of energy, AA, and P and reduced growth performance. Xylanase and phytase can partially ameliorate the reduced nutrient digestibility of diets containing millrun. The improved nutrient digestibility did coincide with improved G:F but did not translate into an improved ADG.

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