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Effects of xylanase supplementation on the apparent digestibility and digestible content of energy, amino acids, phosphorus, and calcium in wheat and wheat by-products from dry milling fed to grower pigs[1,2]

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ABSTRACT: Wheat by-products are feedstuffs that vary in nutritional value, partly because of arabinoxylans that limit nutrient digestibility. Millrun is a by-product from dry milling wheat into flour and contains varying amounts of the bran, middlings, screening, and shorts fractions. The digestible nutrient content of millrun is not well known. Effects of xylanase supplementation (0 or 4,000 units/kg of diet) on energy, AA, P, and Ca digestibilities were studied in a wheat control diet and 5 diets containing 30% of a by-product (millrun, middlings, shorts, screening, or bran) in a 2 × 6 factorial arrangement of treatments. The wheat control diet was formulated to contain 3.34 Mcal of DE/kg and 3.0 g of standardized ileal digestible Lys/Mcal of DE. Diets contained 0.4% chromic oxide. Each of 12 ileal-cannulated pigs (32.5 ± 2.5 kg) was fed 6 or 7 of 12 diets at 3 times the DE requirement for maintenance in successive 10-d periods for 6 or 7 observations per diet. Feces and ileal digesta were each collected for 2 d. Xylanase tended to increase ($P < 0.10$) ileal energy digestibility by 2.2 percentage units and the DE content by 0.10 Mcal/kg of DM and increased ($P < 0.05$) ileal DM digestibility by 2.8 percentage units; a diet × xylanase interaction was not observed. Xylanase increased ($P < 0.05$) total tract energy and DM digestibilities and the DE content. A diet × xylanase interaction was observed; xylanase increased ($P < 0.05$) total tract energy digestibility of the millrun diet from 72.1 to 78.9%, DE content from 3.19 to 3.51 Mcal/kg of DM, and DM digestibility from 71.5 to 78.6%. Diet affected ($P < 0.05$) and xylanase improved ($P < 0.05$) digestibility and digestible contents of some AA in diets and by-products, including Lys, Thr, and Val. Xylanase increased ($P < 0.05$) Lys digestibility by 13.8, 5.0, 5.2, 6.0, and 14.1 percentage units in millrun, middlings, shorts, screening, and bran, respectively. Diet affected ($P < 0.01$) total tract P and Ca digestibilities. Xylanase increased ($P < 0.05$) digestible P and Ca contents. In summary, nutrient digestibility varies among wheat by-products. Millrun contained 2.65 Mcal of DE/kg of DM, which xylanase increased to 3.56 Mcal of DE/kg of DM. Xylanase improved nutrient digestibility and DE content in wheat by-products; and the extent of improvement depended on the by-product. Xylanase supplementation may maximize opportunities to include wheat by-products in swine diets and ameliorate reductions in nutrient digestibility that may be associated with arabinoxylans.

Key words: by-product, digestibility, energy, pig, wheat, xylanase

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INTRODUCTION

Wheat millrun is a by-product of the dry milling of wheat into flour (Holden and Zimmerman, 1991). Millrun generally includes the individual wheat by-products bran, shorts, screening, and middlings (Association of American Feed Control Officials, 1988) and contains 9.5% crude fiber (Dale, 1996). Wheat millrun and other

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[2]A portion of this study was presented at the Digestive Physiology in Pigs conference in Vejle, Denmark, May 25 to 27, 2006, and was included as a short communication in the conference proceedings: Nortey, T. N., J. F. Patience, J. S. Sands, and R. T. Zijlstra. 2007. Xylanase supplementation improves energy digestibility of wheat by-products in grower pigs. Livest. Sci. 109:96–99.

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wheat by-products are alternative feedstuffs for swine, and are readily available in Canada and the United States. However, the digestible nutrient profile of wheat millrun is not well characterized (Nortey et al., 2007).

Wheat contains nonstarch polysaccharides (**NSP**) in the cell wall (Diebold et al., 2004). Wheat by-products have a greater NSP content than does wheat (Slominski et al., 2004). Because of the NSP, nutrients contained in wheat by-products are not utilized well by swine (Sauer et al., 1977), because mammalian digestive enzymes do not hydrolyze NSP (Barrera et al., 2004). The NSP and enclosed nutrients are therefore digested mostly in the large intestine via microbial fermentation (Li et al., 1996). Hindgut fermentation is less efficient for energy utilization than is enzymatic hydrolysis in the small intestine (Noblet et al., 1994). Dietary supplementation of exogenous enzymes such as xylanase may hydrolyze the main NSP of wheat (arabinoxylans) and thereby improve energy utilization by the pig (Diebold et al., 2004).

The hypothesis of the present study was that effects of supplemental xylanase on the digestibility of energy, AA, and P would differ among individual wheat by-products, wheat millrun, and wheat in grower pigs. The objectives were as follows: 1) to measure the digestibilities and digestible contents of GE, AA, P, and Ca of diets containing wheat, wheat millrun, and the individual wheat by-products bran, middlings, screening, and shorts; 2) to calculate the digestibilities of GE, AA, P, and Ca and digestible contents of GE and AA specifically for wheat millrun and by-products; and 3) to study the impact of xylanase supplementation on these variables and whether xylanase would interact with diet and by-products.

MATERIALS AND METHODS

The animal protocol was approved by the University of Saskatchewan Committee on Animal Care and Supply and followed established principles (Canadian Council on Animal Care, 1993). The experiment was conducted at the Prairie Swine Centre Inc. (Saskatoon, Saskatchewan, Canada).

Experimental Design and Diets

The effects of xylanase supplementation (0 or 4,000 units/kg of diet) were studied in a wheat control diet and 5 wheat by-product diets (millrun, middlings, shorts, screening, and bran) in a 2 × 6 factorial arrangement, for a total of 12 diets. An endo-1,4-β-xylanase (EC 3.2.1.8; Porzyme 9300; Danisco Animal Nutrition, Marlborough, UK) was used. The 5 by-products and wheat originated from a commercial flour mill (Dawn Foods, Saskatoon, Saskatchewan, Canada). The millrun used for this study was steam pelleted (Dawn Foods) to reduce bulk density and facilitate transport, and was then reground in a hammer mill across a 4-mm screen (New Life Feeds, Saskatoon, Saskatchewan, Canada) before mixing. The millrun contained the screening, bran, and short fractions, but not the middlings fraction after flour milling of hard red spring wheat, and was the same batch used in an earlier study (Nortey et al., 2007). The other by-products were not processed further before feed manufacturing.

The by-products can be described as follows. The contaminants that are separated from whole wheat seeds before flour milling are collectively called wheat screening and typically consist of malformed wheat kernels, foreign seeds, and other contaminants. Generally, wheat screening contains less than 7% crude fiber and not less than 35% broken or shrunken grain (Audren et al., 2002). The wheat bran is the coarse outer covering of the wheat kernel that is separated from cleaned and scoured wheat in the process of commercial flour milling and contains 12% crude fiber (Association of American Feed Control Officials, 1988). Wheat shorts are the layer of the wheat kernel just inside the outer bran layer covering the endosperm (Huang et al., 1999) and usually contain 5 to 10% crude fiber and 15 to 20% CP. Wheat middlings consist mostly of fine particles of bran and germ and contain at least 15% CP (O'Hearn and Easter, 1983). Wheat millrun consists of coarse bran, shorts, screening, and middlings (Association of American Feed Control Officials, 1988) and contains approximately 9.5% crude fiber (Dale, 1996).

The wheat control diet was formulated to contain 3.34 Mcal of DE/kg and 3.0 g of standardized ileal digestible Lys/Mcal of DE (Table 1). In the wheat control diet, $NaHCO_3$ was included together with salt to maintain Na and ensure that Cl concentration was not elevated because of L-Lys·HCl inclusion rates. The wheat control diet was formulated to meet the estimated requirement for digestible AA, minerals, and vitamins (NRC, 1998), and to be marginally low (60 kcal/kg less) in DE. The by-product diets were produced by mixing the wheat control diet with 30% of the individual wheat by-products. Xylanase was included at 167 g/metric ton of finished feed, reaching an activity of 4,000 units/kg of diet. Chromic oxide (0.4%) was added to the diets as an indigestible marker.

Experimental Procedures

Twelve crossbred barrows (Camborough-22 × Line 65; PIC Canada Ltd., Winnipeg, Manitoba, Canada; initial BW, 32.5 ± 2.5 kg; initial age, 85 ± 7 d) were surgically fitted with a T-cannula at the distal ileum. Pigs were allotted to a 7 × 12 Youden square design (Anderson and McLean, 1974) with 7 periods and 12 pigs. Each experimental period lasted 10 d. During the experiment, 2 pigs were removed, which resulted in 7 observations for 3 diets and 6 observations for 9 diets, for a total of 75 observations.

Pigs were housed in individual metabolism pens as described previously (Nortey et al., 2007). Daily feed allowance was gradually increased for 14 d after surgery to a maximum of 3 times the maintenance for energy (3

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× 110 kcal of DE/kg of $BW^{0.75}$; NRC, 1998), which was fed in 2 equal meals at 0800 and 1600 h, resulting in an ADFI of 1.34, 1.47, 1.66, 1.82, 2.02, 2.24, and 2.45 kg/d during the first through the seventh period, 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 seven 10-d experimental periods consisted of a 6-d acclimation to the experimental diets, followed by a 2-d collection of feces and a 2-d collection of ileal digesta. Pigs were weighed at the beginning of the experimental period (d 0) and at the end of every period thereafter (d 10, 20, 30, 40, 50, and 60) to determine the maintenance requirement that was used to calculate the daily feed allowance in the following period.

Digesta samples were collected for 2 d by using bags containing 5 mL of 10% (vol/vol) formic acid attached to the opened cannula barrel for 10 h. Feces were collected a minimum of 2 times per day at 0800 and 1600 h. Feces were collected by using plastic bags attached to the skin around the anus (Van Kleef et al., 1994). Collected digesta and feces were pooled by pig and frozen at −20°C. Before analyses, feces and digesta were thawed, homogenized, subsampled, and freeze-dried.

Chemical Analyses

Diets and ingredients and freeze-dried feces and digesta were ground finely in a Retsch 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 diets, 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 diets, feces, and digesta was analyzed by using an adiabatic bomb calorimeter (model 5003, Ika-Werke GmbH and Co. KG, Staufen, Germany), and benzoic acid was used as a standard.

Diets and digesta were analyzed for AA except Trp with precolumn derivatization by using phenylisothiocyanate (Guay et al., 2006). Norleucine was used as an internal marker, and, after hydrolysis, the sample was dissolved in distilled water containing EDTA to chelate the metal ions. The Cys was determined as cysteic acid and Met was determined as Met sulfone after preoxidation with performic acid and precolumn derivation by using phenylisothiocyanate (Pierce Inc., Rockford, IL; Guay et al., 2006).

Phosphorus was analyzed in wheat, wheat by-products, diets, digesta, and feces by a spectrophotometer (model 80-2097-62; LKB-Ultraspec III, Pharmacia) at 470 nm after ashing at 600°C (method 965.17; AOAC, 1990). Phytate P content in wheat by-products was analyzed by a spectrophotometer (Ultraspec 2000, Pharmacia) at 519 nm after acidification, boiling after addition of ferric solution, and addition of bipyridine solution (Haug and Lantzsch (1983). The diets, wheat, by-products, digesta, and feces were analyzed for Ca by an atomic absorption spectrophotometer (method 985.01; AOAC, 1990). After grinding over a 0.5-mm screen, diet and wheat by-product samples were analyzed by GLC for soluble and insoluble NSP and constituent sugars (Englyst and Hudson, 1987). Wheat and by-products were analyzed for ADF (method 973.18; AOAC 1990) and NDF (Van Soest et al., 1991).

Based on the results of the chemical analyses, apparent ileal digestibility (**AID**) of AA, total tract digestibility of Ca, ileal and total-tract digestibilities of P, GE, and DM, and DE content were calculated for the 12 diets by using the chromic oxide concentration of diets, digesta, and feces (Adeola, 2001). Ileal digestibility of Ca was not reported because of the occurrence of negative values. The digestibility values of the 5 wheat by-products were separated from the wheat control diet by using the difference method (Fan and Sauer, 1995),

Table 1. Ingredient and nutrient composition (as-fed basis) of the wheat control diet

Item	Wheat control[1]
Ingredient, %	
Wheat	83.26
Soybean meal	12.50
Dicalcium phosphate	1.20
Limestone	0.85
Vitamin premix[2]	0.50
Mineral premix[3]	0.50
L-Lys·HCl	0.49
Sodium bicarbonate	0.29
Salt	0.20
L-Thr	0.15
DL-Met	0.06
Calculated nutrient content	
DE, Mcal/kg	3.34
Standardized digestible Lys,[4] g/Mcal of DE	3.0
Total P, %	0.60
Available P,[5] %	0.41
Phytate P,[6] %	0.27
Ca, %	0.70

[1]The 5 wheat by-product diets were processed by mixing 70% of the wheat control diet with 30% of the wheat by-product. Subsequently, xylanase was included at 167 g/1,000 kg of finished feed to the wheat control and wheat by-product diets to create 12 diets in a 6 × 2 factorial arrangement. The 12 experimental diets were mixed with 0.4% chromic oxide.

[2]Provided the after per kilogram of wheat control 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 after per kilogram of wheat control diet: Zn, 100 mg as $ZnSO_4$; Fe, 80 mg as $FeSO_4$; Cu, 50 mg as $CuSO_4$; Mn, 25 mg as $MnSO_4$; I, 0.5 mg as $Ca(IO_3)_2$; and Se, 0.1 mg as Na_2SeO_3.

[4]Calculated content: 3.0 g of standardized ileal digestible Lys/Mcal of DE (0.94% apparent ileal digestible Lys) and an ideal pattern of standardized digestible Thr and Met to Lys of 60 and 30, respectively (NRC, 1998).

[5]Calculated by using total P content and bioavailability of P (NRC, 1998).

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

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Table 2. Analyzed ADF and NDF and total, insoluble, and soluble nonstarch polysaccharide (NSP) and total P and Ca content (%, as-fed) of wheat and wheat by-products

Item	Wheat	Millrun	Middlings	Screening	Shorts	Bran
ADF	2.8	16.8	7.8	11.5	9.5	12.0
NDF	10.9	38.9	25.4	22.3	29.5	37.9
NSP						
Arabinose						
Total	2.32	5.42	5.78	6.38	2.85	7.95
Insoluble	1.83	4.79	4.67	5.62	2.37	5.72
Soluble[1]	0.48	0.63	1.12	0.75	0.49	2.24
Xylose						
Total	3.32	10.15	8.05	9.06	6.46	12.45
Insoluble	2.70	9.47	6.40	7.84	5.87	8.99
Soluble	0.62	0.68	1.65	1.22	0.60	3.46
Mannose						
Total	0.19	0.27	0.64	0.28	0.22	0.26
Insoluble	0.16	0.23	0.57	0.24	0.20	0.22
Soluble	0.04	0.04	0.07	0.04	0.02	0.04
Glucose						
Total	0.19	9.68	7.09	6.94	11.50	9.40
Insoluble	0.16	10.26	5.74	6.43	11.85	7.93
Soluble	0.04	−0.58	1.35	0.51	−0.36	1.47
Galactose						
Total	0.41	0.67	0.70	0.63	0.64	0.84
Insoluble	0.19	0.54	0.38	0.50	0.45	0.54
Soluble	0.22	0.13	0.32	0.14	0.19	0.30
Nonstarch polysaccharide						
Total	19.05	26.31	22.39	23.39	21.78	31.03
Insoluble	15.11	25.38	17.78	20.67	20.77	23.45
Soluble	3.94	0.93	4.61	2.72	1.01	7.58
Total P	0.37	1.09	0.79	0.36	0.93	1.13
Total Ca	0.05	0.12	0.06	0.03	0.08	0.12

[1]Water-soluble NSP is the difference between total and insoluble NSP.

followed by an identical calculation for digestible contents of energy and AA. The DE fermented in the large intestine was calculated as the difference between total tract and ileal DE contents. The increase in energy digestibility caused by xylanase was calculated as the difference between diets with and without xylanase.

Statistical Analyses

Differences in the digestibilities of energy, AA, Ca, P, and DM among diets were analyzed by using PROC GLM (SAS Inst. Inc., Cary, NC). Diets and by-products were analyzed as a 2 × 6 or a 2 × 5 factorial arrangement, respectively. The statistical model for diets included the following effects: the main factors xylanase (with and without), wheat and by-product diets (6 levels), and their interaction terms, and initial BW as a covariate. The model for by-products contained 5 by-products instead of 6 diets. Treatment means were separated by the probability of difference by using LSMEANS and PDIFF statements in case an interaction or a trend for an interaction between the main factors occurred. In cases of a significant effect for diet or by-product coinciding with a lack of interaction between the main factors, the averaged means for the main factor diet or by-product were separated by the probability of difference by using PDIFF statements. The individual pig was considered as the experimental unit. Differences were considered significant if $P < 0.05$ and were described as tendencies if $0.05 < P < 0.10$.

RESULTS

Nutrient Composition of Wheat By-Products

The wheat by-product samples used for this study varied in fiber, NSP, P, and Ca composition (Table 2). The wheat bran had the greatest total NSP content (31.0% as fed; overall range 19.1 to 31.0%). The millrun sample had the greatest insoluble NSP content (25.4%), and wheat had the least content (15.1%). The contents of arabinose and xylose in by-products followed the observed total NSP content; however, the bran contained a relative greater percentage of soluble NSP. The total P content was greater overall for the wheat by-products than for the wheat, and total Ca was low for all 6 feedstuffs.

The analyzed nutrient composition of the by-product diets reflected the nutrient contents of the wheat and wheat by-products (Table 3). The bran-based diet had the greatest amount of total NSP, followed by the middlings, shorts, millrun, screening, and wheat-control

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Table 3. Analyzed mineral, nonstarch polysaccharide (NSP), AA, and GE composition (as-fed basis) of the wheat control and wheat by-product diets

		Wheat by-product				
Item	Wheat control	Millrun	Middlings	Shorts	Screening	Bran
Mineral content, %						
Total P	0.66	0.79	0.70	0.57	0.74	0.80
Phytate P	0.29	0.52	0.38	0.27	0.48	0.59
Total Ca	0.66	0.45	0.48	0.43	0.37	0.38
NSP content, %						
Insoluble	6.28	11.65	9.94	11.18	8.99	12.39
Soluble[1]	1.77	1.85	2.79	1.23	2.12	2.83
Total	8.24	13.5	12.73	12.40	11.11	15.22
Arabinose						
Insoluble	1.47	2.81	2.44	2.81	1.84	3.11
Soluble	0.48	0.41	0.80	0.12	0.50	0.68
Total	1.95	3.21	3.24	2.93	2.34	3.79
Xylose						
Insoluble	2.16	4.31	3.69	4.25	3.09	4.74
Soluble	0.52	0.62	0.83	0.31	0.77	1.06
Total	2.68	4.94	4.53	4.56	3.86	5.80
AA content, %						
Ala	0.72	0.79	0.83	0.80	0.78	0.69
Arg	0.95	1.07	1.03	1.08	1.04	0.93
Asp	1.32	1.22	1.27	1.32	1.24	1.20
Cys	0.37	0.37	0.34	0.35	0.33	0.30
Glu	5.09	4.68	4.50	4.80	4.47	4.66
Gly	0.77	0.85	0.83	0.84	0.81	0.76
His	0.49	0.54	0.53	0.53	0.52	0.49
Ile	0.78	0.73	0.70	0.73	0.74	0.72
Leu	1.31	1.27	1.22	1.28	1.25	1.23
Lys	1.24	1.08	1.05	1.10	1.15	1.01
Met	0.36	0.34	0.35	0.36	0.35	0.34
Phe	0.90	0.85	0.82	0.88	0.83	0.83
Pro	1.64	1.59	1.52	1.62	1.52	1.54
Ser	0.92	0.91	0.88	0.88	0.85	0.89
Thr	0.68	0.69	0.67	0.69	0.73	0.63
Tyr	0.37	0.44	0.42	0.43	0.41	0.42
Val	0.85	0.86	0.82	0.87	0.84	0.79
GE content, Mcal/kg	3.91	4.03	4.06	4.05	4.00	4.04

[1]Water-soluble NSP is the difference between total and insoluble NSP.

diets. Analyzed phytate P content was greatest in the bran-based diet, followed by the millrun-based diet, and was least in the shorts-based diet. The by-product diets were similar to the wheat-control diet in AA and GE contents.

Energy and Nutrient in Diets

Energy and DM Digestibility. Diet affected ($P < 0.01$; Table 4) and xylanase tended to improve ($P < 0.10$) ileal energy digestibility and DE content; a diet × xylanase interaction was not observed. Diet affected ($P < 0.01$) and xylanase improved ($P < 0.05$) ileal DM digestibility. Specifically, the wheat diet had the greatest ($P < 0.05$) ileal energy, DM digestibility, and DE content, whereas the middlings diet had the least.

Diet and xylanase interacted ($P < 0.05$) for total tract energy and DM digestibility and DE content; diet and xylanase affected ($P < 0.05$) these 3 total tract digestibility variables. Specifically, xylanase improved ($P < 0.05$) total tract energy digestibility by 6.8 percentage units, DM digestibility by 7.1%, and DE content by 0.32 Mcal/kg of DM for the millrun diet, but not for the other diets. Xylanase did not affect the DE content of the wheat diet. Total tract energy digestibility was greater ($P < 0.05$) for the wheat diet than for the middlings and bran diets. Diet tended to affect ($P < 0.10$) the energy fermented in the large intestine, whereas xylanase did not.

Ileal AA Digestibility. Xylanase interacted with diet ($P < 0.05$; Table 5) to increase the AID of Ala, Arg, His, Leu, Lys, Phe, Thr, Tyr, and Val, and tended to affect ($P < 0.10$) the AID for Cys, Gly, Ile, Met, and Ser. Specifically, xylanase improved ($P < 0.05$) the AID of Ala, Gly, Leu, Lys, Thr, and Val of the bran diet, and increased ($P < 0.05$) the AID of Ala of the millrun diet. In the diets without xylanase, the AID of Lys was greatest ($P < 0.05$) in the wheat diet and least in the middlings and bran diets.

P and Ca Digestibility. Diet affected ($P < 0.01$; Table 6) apparent ileal P digestibility, and xylanase did not. Diet and xylanase interacted to affect ($P < 0.05$)

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Table 4. Effects of wheat and wheat by-product diets and xylanase supplementation on apparent ileal and total tract energy and DM digestibility and DE content in grower pigs[1]

		Diet							*P*-value		
Item	XYL[2]	Wheat	Millrun	Middlings	Shorts	Screening	Bran	Pooled SEM	Diet	XYL	Diet × XYL
Ileal digestibility											
Energy, %	−	71.9^{f}	66.6^{fg}	63.1^{h}	65.4^{gh}	65.2^{gh}	69.0^{f}	2.25	<0.001	0.090	0.505
	+	71.8^{f}	73.7^{fg}	61.9^{h}	67.0^{gh}	66.5^{gh}	73.4^{f}				
DE, Mcal/kg of DM	−	3.11^{f}	2.89^{fg}	2.82^{h}	2.91^{fgh}	2.89^{gh}	2.97^{f}	0.09	0.002	0.090	0.406
	+	3.12^{f}	3.19^{fg}	2.75^{h}	2.98^{fgh}	2.92^{gh}	3.25^{f}				
DM, %	−	71.9^{f}	61.7^{g}	61.2^{h}	63.4^{gh}	63.3^{gh}	65.1^{fg}	2.30	<0.001	0.038	0.116
	+	69.7^{f}	69.9^{g}	61.7^{h}	64.5^{gh}	65.0^{gh}	71.7^{fg}				
Total tract digestibility											
Energy, %	−	81.8^{a}	72.1^{d}	75.7^{bcd}	76.2^{bcd}	78.0^{abc}	73.1^{cd}	1.23	<0.001	0.015	0.050
	+	81.5^{a}	78.9^{ab}	76.4^{bcd}	77.1^{abcd}	79.1^{ab}	74.4^{bcd}				
DE, Mcal/kg of DM	−	3.54^{a}	3.19^{d}	3.37^{abcd}	3.38^{abcd}	3.45^{abc}	3.25^{cd}	0.05	<0.001	0.026	0.031
	+	3.53^{a}	3.51^{ab}	3.39^{abcd}	3.43^{abcd}	3.47^{abc}	3.29^{bcd}				
DM, %	−	81.5^{a}	71.5^{e}	74.6^{cde}	75.9^{bcde}	77.6^{abc}	72.1^{de}	1.21	<0.001	0.003	<0.001
	+	81.1^{ab}	78.6^{abc}	75.8^{cde}	76.9^{abcd}	78.8^{abc}	73.6^{cde}				
DE fermented in large intestine[3]											
Mcal/kg of DM	−	0.42	0.40	0.55	0.47	0.69	0.34	0.12	0.071	0.906	0.934
	+	0.42	0.29	0.63	0.45	0.55	0.22				

[a–e]Means for the same item with the same letter are not different ($P > 0.05$).

[f–h]Averaged means for the 6 diets for the same item with the same letter are not different ($P > 0.05$).

[1]Twelve pigs (32.5 ± 2.5 kg), each fed 7 diets at 3 times the maintenance requirement for energy in the subsequent 7 periods. Treatment means are reported as least squares means and are based on 6 observations per mean, except for 7 observations for the after 3 means: wheat with xylanase, millrun without xylanase, and screening with xylanase. XYL = xylanase.

[2]A minus (−) indicates without xylanase; a plus (+) indicates with 4,000 units of xylanase/kg of diet.

[3]Calculated difference of total tract and ileal DE content.

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Table 5. Effects of wheat and wheat by-product diets and xylanase supplementation on apparent ileal AA digestibility in grower pigs[1]

Ileal AA digestibility, %	XYL[2]	Diet						Pooled SEM	*P*-value		
		Wheat	Millrun	Middlings	Shorts	Screening	Bran		Diet	XYL	Diet × XYL
Ala	−	70.4^{a}	61.5^{b}	64.9^{ab}	69.4^{ab}	66.5^{ab}	59.6^{c}	2.41	0.676	0.019	0.026
	+	67.4^{ab}	72.7^{a}	67.9^{ab}	65.9^{ab}	69.8^{ab}	70.0^{ab}				
Arg	−	83.7^{ab}	83.5^{ab}	82.5^{ab}	83.5^{ab}	82.5^{ab}	79.8^{b}	1.27	0.088	0.255	0.012
	+	79.7^{b}	87.5^{a}	82.0^{ab}	83.4^{ab}	83.4^{ab}	84.8^{ab}				
Asp	−	76.5	71.0	69.0	71.3	71.4	64.9	2.43	0.060	0.606	0.134
	+	72.7	75.6	66.5	71.0	69.8	72.7				
Cys	−	77.6^{a}	70.7^{abc}	66.2^{abc}	73.1^{abc}	65.7^{c}	61.5^{b}	2.56	<0.001	0.776	0.055
	+	74.0^{ab}	73.4^{abc}	62.9^{bc}	67.1^{abc}	68.8^{abc}	71.2^{ab}				
Glu	−	85.1	86.1	85.4	85.8	81.2	84.5	1.51	0.080	0.159	0.488
	+	87.1	87.9	85.1	86.0	83.3	89.0				
Gly	−	72.8^{a}	64.7^{bc}	59.1^{c}	66.6^{ab}	60.9^{bc}	59.8^{c}	2.73	0.085	0.645	0.065
	+	69.3^{ab}	68.8^{ab}	60.4^{c}	61.4^{c}	65.2^{bc}	66.9^{b}				
His	−	80.7^{ab}	77.3^{ab}	76.8^{ab}	79.1^{ab}	77.3^{ab}	73.8^{b}	1.62	0.352	0.211	0.009
	+	77.8^{ab}	82.7^{a}	76.4^{ab}	76.2^{ab}	77.4^{ab}	81.3^{ab}				
Ile	−	82.7	80.6	78.6	80.6	78.9	76.8	1.55	0.402	0.421	0.066
	+	80.1	82.6	79.1	78.2	79.8	82.9				
Leu	−	82.9^{ab}	80.6^{ab}	79.4^{ab}	80.8^{ab}	79.3^{ab}	76.5^{b}	1.44	0.317	0.160	0.017
	+	80.3^{ab}	83.9^{a}	79.5^{ab}	79.4^{ab}	79.9^{ab}	83.5^{a}				
Lys	−	86.8^{a}	81.3^{abcd}	78.9^{cd}	81.6^{abcd}	84.2^{abc}	76.9^{d}	1.20	<0.001	0.005	0.001
	+	84.3^{abc}	85.1^{ab}	80.7^{bcd}	81.9^{abcd}	84.3^{abc}	82.9^{abc}				
Met	−	82.9^{a}	77.4^{ab}	75.6^{ab}	75.0^{ab}	71.4^{b}	75.6^{ab}	2.31	0.011	0.205	0.064
	+	80.9^{ab}	78.8^{ab}	72.0^{ab}	78.7^{ab}	77.2^{ab}	80.3^{ab}				
Phe	−	83.7^{ab}	81.3^{ab}	80.0^{ab}	81.5^{ab}	79.4^{ab}	78.1^{b}	1.37	0.068	0.076	0.035
	+	81.7^{ab}	85.5^{a}	79.9^{ab}	81.3^{ab}	80.1^{ab}	84.2^{ab}				
Pro	−	83.8	81.4	78.1	84.4	81.8	79.6	2.53	0.233	0.681	0.376
	+	80.3	85.2	76.9	82.6	81.8	85.9				
Ser	−	76.8^{a}	73.2^{ab}	70.7^{ab}	72.9^{ab}	62.3^{b}	68.6^{ab}	2.75	0.045	0.164	0.059
	+	76.1^{a}	76.8^{a}	69.9^{ab}	69.5^{ab}	72.1^{ab}	76.6^{a}				
Thr	−	77.5^{a}	72.2^{ab}	67.2^{bc}	70.7^{abc}	76.5^{ab}	62.9^{c}	2.06	<0.001	0.188	0.005
	+	74.0^{ab}	76.6^{ab}	68.9^{abc}	69.9^{abc}	73.1^{ab}	73.5^{ab}				
Tyr	−	76.4^{b}	78.3^{ab}	74.9^{abc}	75.3^{abc}	77.7^{ab}	71.3^{bc}	1.72	0.014	0.073	0.010
	+	74.2^{bc}	82.3^{a}	74.4^{abc}	76.3^{ab}	76.8^{ab}	80.5^{ab}				
Val	−	79.2^{ab}	76.5^{abc}	73.7^{bc}	76.8^{abc}	76.0^{abc}	70.3^{c}	1.58	0.037	0.117	0.004
	+	75.7^{abc}	81.4^{a}	74.3^{abc}	75.0^{abc}	76.3^{abc}	78.7^{ab}				

[a–d]Means within the same item with the same superscript letter are not different ($P > 0.05$).

[1]Twelve pigs (32.5 ± 2.5 kg), each fed 7 diets at 3 times the maintenance requirement for energy in the subsequent 7 periods. Treatment means are reported as least squares means and are based on 6 observations per mean, except for 7 observations for the after 3 means: wheat with xylanase, millrun without xylanase, and screening with xylanase. XYL = xylanase.

[2]A minus (−) indicates without xylanase; a plus (+) indicates with 4,000 units of xylanase/kg of diet.

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apparent total tract P digestibility. In the diets without xylanase, the millrun diet had a 15 percentage unit lesser ($P < 0.05$) apparent total tract P digestibility than did the wheat diet. Xylanase did not affect apparent total tract P digestibility for any of the diets. Diet affected ($P < 0.01$) apparent total tract Ca digestibility, and xylanase did not. The wheat diet had a greater ($P < 0.05$) Ca digestibility than did the by-product diets. Xylanase and diet interacted ($P < 0.05$) for total tract digestible P content. Xylanase improved ($P < 0.05$) total tract P content for the millrun diet by 1.2 g/kg of DM, but did not for any of the other diets. Diet affected ($P < 0.01$) total tract digestible Ca content, and xylanase did not. The greatest total tract digestible Ca content was for the wheat diet.

Energy and Nutrients in Wheat By-products

Energy and DM Digestibility. By-products tended to affect ($P < 0.10$; Table 7) ileal energy digestibility. Xylanase did not affect ileal energy digestibility and DE content; a by-product × xylanase interaction was not observed. Xylanase increased ($P < 0.05$) ileal DM digestibility of the by-products; a by-product × xylanase interaction was not observed.

Xylanase increased ($P < 0.05$) total tract energy and DM digestibility and the DE content of by-products. By-products affected ($P < 0.05$) total tract DM digestibility, and tended to affect DE content of by-products. Total tract DM digestibility was greater ($P < 0.05$) for the screening than for the middling and bran.

Ileal AA Digestibility. Xylanase increased ($P < 0.05$; Table 8) the AID of Arg, Ile, Leu, Lys, Phe, Ser, Thr, Tyr, and Val, and tended to increase ($P < 0.10$) the AID of Ala and His. By-products affected ($P < 0.05$) the AID of Glu, Lys, Pro, Ser, Thr, Tyr, and Val. For example, the AID of Lys was greater ($P < 0.05$) for screening than bran.

Xylanase and by-product interacted ($P < 0.05$) to affect the AID content of Tyr. Xylanase increased ($P < 0.05$; Table 9) the digestible AA content of Ala, Arg, Gly, His, Ile, Leu, Lys, Met, Phe, Ser, Thr, Tyr, and Val. By-products affected ($P < 0.05$) the digestible AA content of Ala, Arg, Asp, Cys, Glu, Gly, His, Ile, Leu, Lys, Phe, Pro, Ser, Thr, Tyr, and Val. For example, the digestible content of Thr was greater ($P < 0.05$) for screening than millrun, shorts, bran, and middlings. A by-product × xylanase interaction affected ($P < 0.05$) the digestible AA content of Arg, His, Ile, Lys, Met, and Tyr, caused in most cases by a lack of a xylanase effect for shorts.

P and Ca Digestibility. By-products affected ($P < 0.01$; Table 10) apparent total tract P and Ca digestibilities. Specifically, bran had greater ($P < 0.05$) total tract P and Ca digestibilities than did millrun, middlings, and screening. Xylanase did not affect apparent total tract P and Ca digestibilities.

DISCUSSION

In the present study, the addition of wheat millrun or by-products to a wheat-based diet for grower pigs reduced DE content and energy and nutrient digestibilities. Supplemental xylanase did not affect the digestibility of nutrients in the wheat-based diet, but did improve the DE content and nutrient digestibility of the by-product diets. Diet and by-product interacted with xylanase supplementation for some of the variables, and millrun responded best to xylanase supplementation.

By-product Addition

The inclusion of wheat by-products reduced DE content and energy, AA, and DM digestibility. The reduced digestibility was due to a greater content of fiber in by-products than in the parent grain (Slominski et al., 2004), which pigs do not digest well. The main NSP in wheat and wheat by-products are arabinoxylans (Zijlstra et al. 1999), which can act as an antinutritional factor (Bell et al., 1983; Stanogias and Pearce, 1985) that can compromise the digestibility of other nutrients. The reduction in nutrient digestibility and DE content varied among the different diets and individual by-products, a variation likely attributable to the different chemical compositions among the by-products, including their soluble, insoluble, and total NSP content. The proportion of total tract DE content that was fermented in the hindgut differed among diets, reflecting the different amounts of fiber that were fermented. Hindgut fermentation results in VFA that have nutritional value for pigs (Noblet et al., 1994).

By-product addition reduced apparent ileal AA digestibility, and this was likely due to the increased NSP and phytate content. Increased endogenous losses of AA attributable to NSP are likely part of the explanation (Schulze et al., 1995; Souffrant, 2001). Wheat by-products have greater contents of protein (Slominski, et al., 2004) and AA (NRC, 1998) than does wheat grain. However, for the extra AA to be beneficial to the pig, the AA have to be available for hydrolysis by the endogenous enzymes within the porcine gastrointestinal tract. In the present study, the measured AID for Lys for middlings and shorts were 8 and 2 percentage units less, respectively, than the 75 and 73% reported in NRC (1998); however, the measured AID for Lys in shorts was 9 percentage units greater than the 62% measured by Huang et al. (1999). The differences in Lys AID further illustrate differences in nutritional value among wheat by-product samples. Different wheat protein characteristics and properties among by-products might play a further role (Veraverbeke and Delcour, 2002).

By-product inclusion reduced apparent P and Ca digestibilities. The P in plant-based feedstuffs is mainly in the form of phytate P, which is not readily avail-

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Table 6. Effects of wheat and wheat by-product diets and xylanase supplementation on apparent ileal and total-tract P and Ca digestibility and content in grower pigs[1]

Item	XYL[2]	Diet						Pooled SEM	*P*-value		
		Wheat	Millrun	Middlings	Shorts	Screening	Bran		Diet	XYL	Diet × XYL
Ileal digestibility, %											
P	−	51.7[ef]	30.9[g]	29.8[g]	34.4[g]	39.8[fg]	52.9[e]	4.5	0.003	0.155	0.131
	+	44.9[ef]	47.4[g]	36.2[g]	42.2[g]	43.0[fg]	48.1[e]				
Total tract digestibility, %											
P	−	52.4[a]	37.4[b]	43.8[ab]	42.1[ab]	46.9[ab]	47.8[ab]	2.8	0.029	0.223	0.045
	+	49.8[ab]	50.7[ab]	41.5[ab]	46.0[ab]	45.6[ab]	49.0[ab]				
Ca	−	65.8[e]	39.7[fg]	42.8[g]	45.7[g]	48.3[fg]	58.6[ef]	4.3	<0.001	0.524	0.178
	+	63.6[e]	56.0[fg]	44.7[g]	42.3[g]	48.2[fg]	54.9[ef]				
Total tract digestible minerals, g/kg of DM											
P	−	3.9[abc]	3.2[c]	3.9[abc]	3.3[abc]	3.7[abc]	3.0[bc]	0.2	0.009	0.172	0.023
	+	3.7[abc]	4.4[a]	3.6[ab]	3.8[abc]	3.6[abc]	3.0[bc]				
Ca	−	5.6[e]	1.9[fg]	2.1[g]	1.9[g]	2.4[fg]	2.8[f]	0.2	<0.001	0.661	0.174
	+	5.4[e]	2.7[fg]	2.0[g]	1.8[g]	2.4[fg]	2.5[f]				

[a–c]Means within the same item with the same superscript letter are not different ($P > 0.05$).

[e–g]Averaged means for the 6 diets for the same item with the same letter are not different ($P > 0.05$).

[1]Twelve pigs (32.5 ± 2.5 kg) each fed 7 diets at 3 times the maintenance requirement for energy in the subsequent 7 periods. Treatment means are reported as least squares means and are based on 6 observations per mean, except for 7 observations for the after 3 means: wheat with xylanase, millrun without xylanase, and screening with xylanase. XYL = xylanase.

[2]A minus (−) indicates without xylanase; a plus (+) indicates with 4,000 units of xylanase/kg of diet.

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Table 7. Effects of xylanase supplementation on the apparent ileal and total tract energy and DM digestibility and DE content of wheat by-products fed to grower pigs[1]

		By-product						*P*-value		
Item	XYL[2]	Millrun	Middlings	Shorts	Screening	Bran	Pooled SEM	By-product	XYL	By-product × XYL
Ileal digestibility										
Energy, %	−	51.4	41.8	50.3	49.4	62.7	7.90	0.066	0.220	0.647
	+	71.4	38.8	55.9	54.3	65.2				
DE, Mcal/kg of DM	−	2.42	2.09	2.43	2.35	2.61	0.35	0.122	0.205	0.582
	+	3.35	1.89	2.66	2.45	3.01				
DM, %	−	37.1	35.3	42.9	43.4	49.7	7.73	0.296	0.005	0.404
	+	69.4	42.5	52.9	54.1	64.4				
Total tract digestibility										
Energy, %	−	55.8[b]	60.6[ab]	62.7[ab]	69.3[ab]	65.8[ab]	3.42	0.144	0.011	0.096
	+	75.8[a]	64.1[ab]	67.2[ab]	73.5[a]	66.4[ab]				
DE, Mcal/kg of DM	−	2.65	2.95	2.99	3.26	2.61	0.21	0.087	0.005	0.110
	+	3.56	3.01	3.19	3.31	3.11				
DM, %	−	54.9[cd]	59.0[de]	62.9[cd]	68.6[c]	43.2[e]	4.43	0.013	<0.001	0.156
	+	75.2[cd]	63.7[de]	67.4[cd]	73.6[c]	64.8[e]				

[a,b]Means within the same item with the same superscript letter are not different ($P > 0.05$).

[c–e]Averaged means for the 5 by-products for the same item with the same letter are not different ($P > 0.05$).

[1]Twelve pigs (32.5 ± 2.5 kg), each fed 7 diets at 3 times the maintenance requirement for energy in the subsequent 7 periods. Treatment means are reported as least squares means and are based on 6 observations per mean, except for 7 observations for the after 2 means: millrun without xylanase and screening with xylanase. XYL = xylanase.

[2]A minus (−) indicates without xylanase; a plus (+) indicates with 4,000 units of xylanase/kg of diet.

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Table 8. Effects of xylanase supplementation on the apparent ileal AA digestibility of wheat by-products fed to grower pigs[1]

Ileal AA digestibility, %	XYL[2]	By-product: Millrun	Middlings	Shorts	Screening	Bran	Pooled SEM	P-value: By-product	XYL	By-product × XYL
Ala	−	61.1	60.6	67.8	64.7	47.9	6.20	0.338	0.056	0.286
	+	78.4	61.2	61.9	71.9	66.8				
Arg	−	83.6	82.1	86.1	84.0	79.7	2.82	0.547	<0.001	0.213
	+	94.8	87.3	86.6	87.6	93.1				
Asp	−	61.5	51.9	64.9	59.6	50.3	8.44	0.242	0.298	0.679
	+	78.0	50.8	64.9	57.2	64.3				
Cys	−	55.4	46.1	62.8	51.9	41.9	6.60	0.115	0.166	0.663
	+	63.9	46.8	62.0	57.2	59.2				
Glu	−	81.5[ef]	80.1[ef]	82.3[ef]	72.6[f]	84.4[e]	4.81	0.032	0.256	0.819
	+	89.9[ef]	80.5[ef]	82.1[ef]	74.4[f]	92.3[e]				
Gly	−	61.3	37.1	55.7	52.2	42.3	8.96	0.203	0.222	0.908
	+	72.9	44.2	55.8	57.3	58.5				
His	−	76.6	70.0	75.9	73.4	71.1	4.69	0.149	0.057	0.369
	+	88.9	73.0	73.7	74.2	85.7				
Ile	−	77.1	74.1	75.4	70.3	71.4	5.45	0.630	0.044	0.818
	+	84.7	81.7	75.3	76.0	83.6				
Leu	−	78.4	75.4	75.8	77.1	73.3	4.20	0.399	0.020	0.398
	+	89.6	77.7	77.4	79.2	88.4				
Lys	−	73.1[ef]	66.8[f]	71.0[f]	78.2[e]	62.9[f]	3.50	0.002	<0.001	0.536
	+	87.0[ef]	72.3[f]	76.4[f]	84.2[e]	76.6[f]				
Met	−	69.2	58.7	59.9	60.9	68.5	6.51	0.167	0.422	0.979
	+	74.0	57.5	66.8	63.9	74.4				
Phe	−	75.5	73.3	78.5	75.0	72.9	4.04	0.178	0.006	0.180
	+	92.0	75.7	80.3	76.3	87.2				
Pro	−	85.1[e]	65.4[f]	86.2[ef]	76.6[ef]	81.7[ef]	8.33	0.026	0.413	0.970
	+	94.2[e]	65.5[f]	87.4[ef]	78.9[ef]	92.4[ef]				
Ser	−	65.1[e]	59.2[f]	62.8[ef]	57.6[ef]	66.9[e]	5.60	0.047	0.035	0.393
	+	80.6[e]	62.1[f]	60.7[ef]	65.2[ef]	82.2[e]				
Thr	−	63.7[e]	50.3[f]	57.2[f]	73.6[e]	48.6[f]	6.05	0.001	0.020	0.445
	+	82.7[e]	53.6[f]	62.7[f]	73.6[e]	66.9[f]				
Tyr	−	83.9[abc]	73.0[cd]	72.3[c]	78.5[bc]	60.0[d]	4.80	0.009	<0.001	0.013
	+	97.9[a]	74.2[cd]	84.2[abc]	81.6[bc]	93.5[ab]				
Val	−	72.9[bc]	65.4[bc]	73.2[bc]	73.9[b]	57.9[c]	4.72	0.010	0.019	0.062
	+	91.2[a]	63.9[bc]	71.2[bc]	74.9[b]	78.5[b]				

[a–d]Means within the same item with the same superscript letter are not different ($P > 0.05$).

[e–f]Averaged means for the 5 by-products for the same item with the same letter are not different ($P > 0.05$).

[1]Twelve pigs (32.5 ± 2.5 kg) each fed 7 diets at 3 x maintenance requirement for energy in subsequent 7 periods. Treatment means are reported as least squares means and are based on 6 observations per mean, except 7 observations for the after 2 means: millrun without xylanase and screening with xylanase. XYL = xylanase.

[2]A minus (−) indicates without xylanase; a plus (+) indicates with 4,000 units of xylanase/kg of diet.

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Table 9. Effects of xylanase supplementation on the apparent ileal digestible AA content of wheat by-products fed to grower pigs[1]

Ileal digestible AA, g/kg of DM	XYL[2]	By-product: Millrun	Middlings	Shorts	Screening	Bran	Pooled SEM	P-value: By-product	XYL	By-product × XYL
Ala	−	0.57^{ab}	0.56^{ab}	0.68^{a}	0.53^{ab}	0.29^{c}	0.054	<0.001	0.002	0.059
	+	0.77^{a}	0.72^{a}	0.60^{ab}	0.68^{a}	0.43^{bc}				
Arg	−	1.06^{cd}	0.84^{e}	1.12^{cd}	1.01^{d}	0.62^{f}	0.034	<0.001	<0.001	0.002
	+	1.45^{a}	1.19^{bc}	1.28^{b}	1.14^{c}	0.88^{e}				
Asp	−	0.50^{gh}	0.55^{h}	0.86^{g}	0.62^{h}	0.45^{h}	0.100	0.007	0.118	0.277
	+	0.93^{gh}	0.57^{h}	0.85^{g}	0.60^{h}	0.56^{h}				
Cys	−	0.22^{g}	0.22^{gh}	0.20^{h}	0.10^{i}	0.07^{i}	0.104	<0.001	0.435	0.162
	+	0.26^{g}	0.20^{gh}	0.15^{h}	0.14^{i}	0.11^{i}				
Glu	−	3.02^{g}	2.34^{h}	3.36^{g}	1.91^{h}	3.07^{g}	0.241	<0.001	0.735	0.898
	+	3.36^{g}	2.33^{h}	3.22^{g}	2.02^{h}	3.10^{g}				
Gly	−	0.59^{g}	0.37^{h}	0.62^{g}	0.37^{h}	0.31^{h}	0.067	<0.001	0.019	0.662
	+	0.73^{g}	0.51^{h}	0.61^{g}	0.51^{h}	0.46^{h}				
His	−	0.51^{b}	0.37^{c}	0.49^{b}	0.41^{bc}	0.30^{d}	0.024	<0.001	<0.001	0.034
	+	0.58^{a}	0.49^{b}	0.47^{bc}	0.45^{bc}	0.42^{bc}				
Ile	−	0.48^{ab}	0.29^{c}	0.49^{ab}	0.51^{a}	0.38^{b}	0.029	<0.001	<0.001	0.006
	+	0.51^{a}	0.46^{ab}	0.47^{ab}	0.52^{a}	0.52^{a}				
Leu	−	0.89^{g}	0.67^{h}	0.95^{g}	0.81^{h}	0.69^{h}	0.059	0.002	0.001	0.201
	+	1.10^{g}	0.83^{h}	0.96^{g}	0.86^{h}	0.93^{h}				
Lys	−	0.40^{d}	0.10^{f}	0.40^{d}	0.65^{bc}	0.20^{ef}	0.039	<0.001	<0.001	<0.001
	+	0.75^{ab}	0.56^{c}	0.68^{bc}	0.84^{a}	0.30^{de}				
Met	−	0.19^{ab}	0.19^{ab}	0.16^{b}	0.17^{ab}	0.15^{b}	0.024	0.531	<0.001	0.013
	+	0.24^{ab}	0.16^{b}	0.27^{a}	0.23^{ab}	0.27^{a}				
Phe	−	0.53^{g}	0.41^{i}	0.62^{g}	0.46^{hi}	0.49^{h}	0.035	<0.001	0.007	0.158
	+	0.72^{g}	0.46^{i}	0.64^{g}	0.46^{hi}	0.56^{h}				
Pro	−	1.14^{g}	0.77^{i}	1.39^{g}	0.97^{hi}	0.89^{h}	0.120	0.026	0.412	0.970
	+	1.54^{g}	0.89^{i}	1.39^{g}	1.03^{hi}	1.29^{h}				
Ser	−	0.58^{ab}	0.43^{bc}	0.53^{b}	0.28^{c}	0.49^{b}	0.048	<0.001	0.022	0.053
	+	0.75^{a}	0.47^{bc}	0.41^{bc}	0.44^{bc}	0.61^{ab}				
Thr	−	0.39^{h}	0.21^{j}	0.34^{i}	0.67^{g}	0.18^{j}	0.044	0.001	0.020	0.445
	+	0.60^{h}	0.43^{j}	0.54^{i}	0.63^{g}	0.40^{j}				
Tyr	−	0.45^{bc}	0.33^{d}	0.35^{d}	0.39^{d}	0.19^{e}	0.022	0.009	<0.001	0.013
	+	0.64^{a}	0.49^{b}	0.52^{b}	0.46^{bc}	0.62^{a}				
Val	−	0.61^{b}	0.41^{c}	0.68^{b}	0.60^{b}	0.34^{c}	0.038	0.011	0.019	0.062
	+	0.87^{a}	0.55^{b}	0.67^{b}	0.63^{b}	0.52^{b}				

[a–f]Means within the same item with the same superscript letter are not different ($P > 0.05$).

[g–j]Averaged means for the 5 by-products for the same item with the same letter are not different ($P > 0.05$).

[1]Twelve pigs (32.5 ± 2.5 kg), each fed 7 diets at 3 times the maintenance requirement for energy in the subsequent 7 periods. Treatment means are reported as least squares means and are based on 6 observations per mean, except for 7 observations for the after 2 means: millrun without xylanase and screening with xylanase. XYL = xylanase.

[2]A minus (−) indicates without xylanase; a plus (+) indicates with 4,000 units of xylanase/kg of diet.

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able (Simons et al., 1990; Liao et al., 2005) because pigs do not produce the endogenous enzymes necessary to digest phytate P (Golovan et al., 2001). Increasing dietary inclusion of by-products, and consequently phytate, could thus reduce digestibilities of P and other nutrients, such as AA and minerals (Selle et al., 2000). The total tract digestibility of P differed among by-products, reflecting differences in the amount of total and phytate P. An increased amount of plant phytate P also means that more of the Ca present will be bound to phytate to form phytin, which is the Ca and Mg salt of phytic acid (Oatway et al., 2001), thereby reducing apparent total tract Ca digestibility. The reduced apparent P digestibility in millrun diets might be further explained by the 30% lesser contents of inorganic P and Ca in the by-product diets compared with the wheat diet. The average 0.05 percentage unit difference in total P content between the wheat and by-product diets (0.74 vs. 0.79 g/kg of DM, respectively; calculated by dividing total tract digestible P content with digestibility) was likely of lesser concern; however, large differences in total P content could affect apparent P digestibility (Ajakaiye et al. 2003).

Xylanase Supplementation

Xylanase improved energy and DM digestibilities and DE content. In the present study, the greatest improvement in nutrient digestibility with xylanase occurred in the by-product diets, whereas little improvement was observed for the diet solely based on wheat. The greater improvement for by-products might be due to greater insoluble and total NSP contents in the by-product diets, thereby presenting more substrate for the xylanase to hydrolyze, as evidenced by the strong relationship between insoluble NSP and the increase in energy digestibility provided by xylanase. Xylanase may improve the nutritional value of high-NSP diets by partially hydrolyzing soluble and insoluble NSP, decreasing digesta viscosity, and rupturing NSP-containing cell walls and thereby releasing their contents for enzymatic hydrolysis (Diebold et al., 2004). Xylanase randomly cuts the arabinoxylan backbone into small fragments and reduces their molecular weights (Tapingkae et al., 2008). Logically, a greater arabinoxylan content in a feed or feedstuff will increase the quantity of entrapped nutrients and thus provide a greater positive effect after xylanase supplementation.

The response to xylanase supplementation was consistently greater for the millrun diet than for either the wheat control or other by-product diets. One explanation might be that millrun was the sole by-product that had been steam-pelleted before feed mixing. Cereal grains contain endogenous enzymes, including xylanase, and endogenous xylanase activity in steam-pelleted diets might be less than in mash diets (Cowieson et al., 2005) because of heat-induced xylanase inactivation. Therefore, pelleting wheat millrun in the present study could have inactivated endogenous xylanase

Table 10. Effects of xylanase supplementation on the apparent total tract P and Ca digestibility of wheat by-products fed to grower pigs[1]

Total tract digestibility	XYL[2]	By-product					Pooled SEM	*P*-value		
		Millrun	Middlings	Shorts	Screening	Bran		By-product	XYL	By-product × XYL
P, %	−	32.9[b]	33.6[b]	45.7[ab]	30.4[b]	60.2[a]	8.42	0.008	0.161	0.989
	+	41.3[b]	42.9[b]	48.2[ab]	41.1[b]	66.8[a]				
Ca, %	−	26.0[b]	12.2[b]	15.5[b]	34.2[b]	65.3[a]	13.3	<0.001	0.104	0.549
	+	37.7[b]	16.3[b]	23.7[b]	39.5[b]	69.5[a]				

[a,b]Averaged means for the 5 by-products for the same item with the same letter are not different ($P > 0.05$).

[1]Twelve pigs (32.5 ± 2.5 kg), each fed 7 diets at 3 times the maintenance requirement for energy in the subsequent 7 periods. Treatment means are reported as least squares means and are based on 6 observations per mean, except for 7 observations for the after 2 means: millrun without xylanase and screening with xylanase. XYL = xylanase.

[2]A minus (−) indicates without xylanase; a plus (+) indicates with 4,000 units of xylanase/kg of diet.

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activity, making millrun more responsive to xylanase supplementation. Furthermore, pelleting can alter the physiochemical properties of fiber, making fiber more degradable with enzymes (Svihus et al., 2004).

Supplementing the diets with xylanase improved the AID of selected AA and total tract P digestibility for the millrun diet, consistent with our earlier study (Nortey et al., 2007). Therefore, the present study provides further evidence that xylanase supplementation increased the P digestibility of wheat by-products (Nortey et al., 2007). Mature grains contain large amounts of phytate P, which is the storage form of plant P (Ravindran et al., 1994). Most of this phytate P is stored in the outermost layers of the seed (i.e., bran and kernel; Maga, 1982), which also contain arabinoxylans. Arabinoxylans are a major substrate for xylanase, and an indirect benefit of adding xylanase to high-arabinoxylan diets is improved P digestibility. Small improvements in P digestibility with xylanase addition translate into improved digestible P values and P utilization. Xylanase also improved the apparent ileal AA digestibility of wheat-based diets in previous studies, indicating that the digestibility of AA may be reduced by the wheat NSP (Barrera et al., 2004). The lack of improvement in Ca digestibility with xylanase was similar to our previous study (Nortey et al., 2007), and might be explained by the decreased amount of wheat and by-products originating from Ca in the experimental diets.

By-product × Xylanase Interaction

The by-product × xylanase interaction on AA and P digestibilities indicated that the extent of response to xylanase depended on the by-product. Complete hydrolysis of wheat arabinoxylans requires the presence of certain enzymatic activities, including xylanases, β-xylosidase, α-arabinofuranosidase, and acetyl and feruloyl esterases (Debyser et al., 1999). The array of enzyme activities is necessary because the linear backbone of arabinoxylans contains β-(1→4)-linked D-xylopyranosol units to which α-arabinofuranosyl units are attached (Tapingkae et al., 2008). The by-products used for the present study contained different proportions of NSP, including arabinose, xylose, and galactose. Variations also existed among the by-products in the difference between total and soluble NSP (i.e., insoluble NSP). These factors may contribute to the different effects of xylanase among by-products.

Cereal grains such as wheat, rye, and barley contain proteins that can inhibit xylanase efficacy (Debyser et al., 1999; Goesaert et al., 2003; Bonnin et al., 2005). Enzyme inhibition is a natural phenomenon that occurs in plant seeds to act as a defense mechanism and regulate plant metabolic processes. The presence of inhibitors can therefore negate effects that can be achieved by adding enzymes to a wheat-based diet for pigs. Most of the effects of endogenous xylanase inhibitors and xylanase have been studied in the food industry in bread making (Debyser et al., 1999); therefore, noninhibited xylanases have been developed to give uniform results in dough formation. The different responses to xylanase supplementation might thus be due to varying concentrations of xylanase inhibitors among the various by-product fractions.

Nutrient digestibility in by-products followed a pattern similar to that of the diets. Xylanase improved energy digestibility and DE content. The measured DE contents of millrun, middlings, shorts, screening, and bran were 2.65, 2.95, 2.99, 3.26, and 2.61 Mcal/kg of DM, respectively. The measured DE content for millrun in the present study was less than assumed previously (2.90 Mcal/kg, as fed; Nortey et al., 2007), and the measured DE content for middlings in the present study was less than the 3.08 Mcal/kg (as fed) reported in NRC (1998), indicating the importance of feed quality analyses before feed mixing. A potential effect of fiber content on digesta passage rate and intestinal microbial activity will require further study.

Wheat by-products combined with exogenous xylanase can potentially replace energy-yielding feedstuffs in swine diets. However, the beneficial effects of xylanase on nutrient digestibility and digestible nutrient content are variable and depend on the by-product. Individual by-products have different fiber compositions that affect xylanase efficacy.

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