Apparent and standardized ileal digestibility of AA and starch in hybrid rye, barley, wheat, and corn fed to growing pigs¹

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ABSTRACT: An experiment was conducted to determine the apparent ileal digestibility (AID) of AA and starch and the standardized ileal digestibility (SID) of AA in three varieties of hybrid rye and in one source of barley, wheat, and corn. Seven growing barrows (initial BW = 26.1 ± 2.4 kg) were randomly allotted to a 7 × 7 Latin square design with seven periods and seven experimental diets. Six diets included one of the grains as the sole source of AA, and an N-free diet was used to determine basal endogenous losses of CP and AA. In each period, ileal digesta were collected for 8 h on days 6 and 7 following a 5-d adaptation period. At the conclusion of the experiment, all ingredients, diets, and ileal digesta samples were analyzed for starch, CP, and AA. The AID of starch was greater ($P < 0.05$) in wheat and corn than in barley or hybrid rye, but all grains had AID values

for starch that were above 95%. Wheat and barley contained more CP and indispensable AA than hybrid rye, but hybrid rye contained more indispensable AA compared with corn. The SID of CP and all indispensable AA was greater ($P < 0.05$) in barley, wheat, and corn than in the three varieties of rye. However, because of the greater concentration of AA in hybrid rye than in corn, the quantities of standardized ileal digestible CP and AA were not different between corn and hybrid rye. In conclusion, hybrid rye has greater concentrations of most AA than corn, but the digestibility of AA in rye is less than in other cereal grains. It is likely that the reason for the reduced SID of AA in rye is that rye contains more fructans and soluble dietary fiber than other cereal grains, which may increase viscosity and reduce the efficiency of endogenous peptidases.

Key words: AA digestibility, cereal grains, hybrid rye, pigs, starch digestibility

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INTRODUCTION

Rye has traditionally not been included in diets fed to pigs in great amounts because most rye in the world is grown for human consumption and primarily used by the grain flour industry for bread making (Bengtsson et al., 1992). Old varieties of rye sometimes contained rye ergots, which prevented usage of large quantities in diets fed to pigs (Friend and Macintyre, 1970). However, with

the advent of hybrid rye and the PollenPlus technology (KWS, Lochow, Germany), which utilizes the Rfp1 restorer gene, the risk of ergot contamination has been reduced (Hackauf et al., 2012; Miedaner and Geiger, 2015).

Rye has high concentrations of nonstarch polysaccharides, which have been correlated with antinutritive properties, especially in young pigs and poultry (Jürgens et al., 2012). However, the fructooligosaccharides in rye are easily fermentable and will, therefore, provide energy for the pig via fermentation in the hindgut. Likewise, the nonstarch polysaccharides in rye may promote greater butyrate production and improve intestinal health (Bach Knudsen et al., 2005, 2016, 2017), and rye may, therefore, have prebiotic effects if included in diets for pigs.

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Historically, production of rye has taken place mainly in northern European countries and production in the Americas has been limited. However, because hybrid rye has greater yields than all other small grains including conventional rye in Europe, it is likely that hybrid rye can also out-yield other small grains such as sorghum, wheat, and barley on the drier soils in the United States and Canada (Jürgens et al., 2012). This may make hybrid rye an interesting ingredient in the feeding of pigs and other livestock species, but at this point, there is limited information about the nutritional value of hybrid rye when fed to pigs. It was, therefore, the objective of this experiment to test the hypothesis that hybrid rye, due to its improved chemical composition, provides ileal digestible quantities of starch, CP, and AA that are comparable to values obtained in barley, wheat, and corn.

MATERIALS AND METHODS

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

Animals, Housing, and Experimental Design

Seven growing barrows (26.1 ± 2.4 kg initial BW) that were the offspring of Line 359 boars and Camborough sows (Pig Improvement Company, Henderson, TN) were prepared with a cannula in the distal ileum as previously described

(Stein et al., 1998). Pigs were housed in individual pens equipped with a tri-bar slatted floor, a feeder, and a nipple waterer. Following a 7-d recovery period from the surgery, animals were allotted to a 7×7 Latin square design with seven periods and seven animals. Animals were assigned to experimental diets in such a way that each diet was fed to only one pig in each period. There were, therefore, a total of seven diets and seven replicate observations per diet.

Three hybrids of rye (KWS Lochow GmbH, Bergen, Germany) and one source of barley, wheat, and corn were used in the experiment. The rye included Bono and Daniello hybrids, which were grown in Germany in 2016, and the Brasetto hybrid, which was grown in Canada in 2016. The barley, wheat, and corn used in the experiment were grown in the United States. Grains were ground using a hammer mill to a mean particle size of approximately 300 microns, and each grain was used in one diet. Thus, three diets containing hybrid rye and one diet containing barley, one diet containing wheat, and one diet containing corn were formulated (Tables 1 and 2). Each diet contained 94% grain as the sole source of starch and AA. Diets also contained 3% soybean oil, and 0.4% chromic oxide was used as an indigestible marker. Vitamins and minerals were included according to estimated nutrient requirements for growing pigs (NRC, 2012). An N-free diet based on cornstarch and sucrose was also included in the experiment to determine basal endogenous losses of CP and AA.

Table 1. Ingredient composition of experimental diets

Ingredient, %	Rye Bono	Rye Daniello	Rye Brasetto	Barley	Wheat	Corn	N free
Cereal grain	94.20	94.20	94.20	94.05	94.15	93.85	—
Cornstarch	—	—	—	—	—	—	68.00
Soybean oil	3.00	3.00	3.00	3.00	3.00	3.00	4.00
Limestone	1.00	1.00	1.00	1.00	1.05	0.60	0.40
Dicalcium phosphate	0.70	0.70	0.70	0.70	0.70	1.45	1.90
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Chromic oxide	0.40	0.40	0.40	0.40	0.40	0.40	0.50
Vitamin–mineral premix ¹	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Solka-floc ²	—	—	—	—	—	—	4.00
Magnesium oxide	—	—	—	—	—	—	0.10
Potassium dioxide	—	—	—	—	—	—	0.40
Sucrose	—	—	—	—	—	—	20.00

¹The vitamin–micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 11,136 IU; vitamin D₃ as cholecalciferol, 2,208 IU; vitamin E as DL- α -tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B₁₂, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper sulfate and copper chloride; Fe, 126 mg as ferrous sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese sulfate; Se, 0.3 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc sulfate.

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Table 2. Analyzed nutrient composition of experimental diets containing three sources of hybrid rye, barley, wheat, or corn, as-fed basis

Calculated values	Rye Bono	Rye Daniello	Rye Brasetto	Barley	Wheat	Corn	N free
DM, %	88.32	89.07	88.29	89.19	89.66	88.94	93.83
CP, %	8.35	8.60	8.37	9.82	10.50	6.70	0.27
Total starch	53.08	51.25	53.53	57.02	56.49	58.61	59.48
Indispensable AA, %							
Arg	0.40	0.43	0.41	0.46	0.51	0.32	0.01
His	0.19	0.19	0.19	0.22	0.24	0.20	0.00
Ile	0.29	0.31	0.30	0.37	0.37	0.25	0.02
Leu	0.53	0.54	0.52	0.68	0.68	0.77	0.03
Lys	0.32	0.33	0.33	0.37	0.34	0.23	0.01
Met	0.13	0.14	0.14	0.16	0.17	0.13	0.00
Phe	0.39	0.41	0.39	0.53	0.47	0.34	0.02
Thr	0.27	0.28	0.27	0.33	0.31	0.25	0.01
Trp	0.07	0.07	0.09	0.10	0.11	0.06	<0.02
Val	0.40	0.42	0.40	0.50	0.48	0.33	0.01
Total	2.99	3.12	3.04	3.72	0.68	2.88	0.11
Dispensable AA, %							
Ala	0.36	0.36	0.35	0.38	0.39	0.49	0.01
Asp	0.57	0.59	0.57	0.58	0.58	0.46	0.04
Cys	0.18	0.18	0.18	0.23	0.23	0.14	0.02
Glu	1.87	1.96	1.84	2.38	2.76	1.21	0.03
Gly	0.36	0.38	0.36	0.39	0.44	0.28	0.01
Pro	0.84	0.87	0.80	1.11	0.97	0.63	0.02
Ser	0.32	0.33	0.32	0.37	0.42	0.30	0.01
Tyr	0.18	0.18	0.18	0.26	0.25	0.20	0.01
Total	4.68	4.85	4.60	5.70	6.04	3.71	0.15
Total amino acids, %	7.86	8.15	7.83	9.63	9.92	6.79	0.44

Feeding and Sample Collection

Feed was provided daily to each pig at the equivalence of 3.2 times the estimated requirement for metabolizable energy for maintenance (i.e., 197 kcal metabolizable energy per kg BW^{0.60}; [NRC, 2012](#)), and water was available at all times. The BW of each pig was recorded at the beginning and at the end of each period. Each period lasted 7 d, with the initial 5 d being an adaptation period to the diets, and ileal digesta were collected for 8 h on days 6 and 7 as previously described ([Stein et al., 1998](#)). All ileal digesta samples were stored at -20 °C immediately after collection.

Chemical Analyses

At the conclusion of each period, ileal digesta samples were mixed within pig and a subsample was collected, lyophilized, and finely ground. The chromium concentration was determined in diets and ileal digesta samples using the Inductive Coupled Plasma Atomic Emission Spectrometric method (method 990.08; [AOAC Int., 2007](#)). Samples were prepared for analysis using nitric acid–perchloric

acid (method 968.08D (b); [AOAC Int., 2007](#)). Crude protein was determined in diets, ingredients, and ileal digesta samples by measuring N concentration using the Kjeldahl method (method 976.05; [AOAC Int., 2007](#)), and DM was determined by oven drying at 135 °C for 2 h (method 930.15; [AOAC Int., 2007](#)). These samples were also analyzed for AA on a Hitachi Amino Acid Analyzer, Model No. L8800 (Hitachi High Technologies America, Inc; Pleasanton, CA) using ninhydrin for postcolumn derivatization and norleucine as the internal standard. Prior to analysis, samples were hydrolyzed with 6N HCl for 24 h at 110 °C (method 982.30 E[a]; [AOAC Int., 2007](#)). Methionine and Cys were determined as Met sulfone and cysteic acid after cold performic acid oxidation overnight before hydrolysis (method 982.30 E[b]; [AOAC Int., 2007](#)). Tryptophan was determined after NaOH hydrolysis for 22 h at 110 °C (method 982.30 E[c]; [AOAC Int., 2007](#)). Total starch was analyzed by the glucoamylase procedure (method 979.10; [AOAC Int., 2007](#)), which yields the enzymatically hydrolyzed starch in the ingredients.

The GE of ingredient samples was measured using an isoperibol bomb calorimeter (Model 6400,

Parr Instruments, Moline, IL). Benzoic acid was used as the standard for calibration. All grain samples were also analyzed for dry ash (method 942.05; [AOAC Int., 2007](#)), and total acid-hydrolyzed ether extract was analyzed by acid hydrolysis using 3N HCl (Ankom^{HCl}, Ankom Technology, Macedon, NY) followed by crude fat extraction using petroleum ether (Ankom^{XT15}, Ankom Technology). Acid detergent fiber and NDF were analyzed using Ankom Technology methods 12 and 13, respectively (Ankom 2000 Fiber Analyzer, Ankom Technology). After ADF analysis, ADL was determined using Ankom Technology method 9 (Ankom Daisy II Incubator, Ankom Technology). Insoluble dietary fiber and soluble dietary fiber were analyzed according to method 991.43 ([AOAC Int., 2007](#)) using the Ankom TDF Fiber Analyzer (Ankom Technology). Total dietary fiber was calculated as the sum of soluble dietary fiber and insoluble dietary fiber. Free monosaccharide concentrations were determined by high-performance liquid chromatography following the procedure by [Smiricky et al. \(2002\)](#), and hydrolyzed monosaccharide concentrations were determined by high-performance liquid chromatography following the procedure by [Bourquin et al. \(1990\)](#) and [Hoebler et al. \(1989\)](#) and corrected for free monosaccharides. Beta-glucans were determined according to method 995.16 ([AOAC Int., 2002](#)). Ingredients were also analyzed for inulin by refractive index high-performance liquid chromatography using a Phenomenex Rezex RHM column (Phenomenex, Inc., Torrance, CA) following a procedure by [Campbell et al. \(1997\)](#). Briefly, 1.0 g of sample was extracted at 85 °C for 15 min, cooled, and analyzed. The mobile phase for pure water had a flow rate of 0.6 mL/min.

Aspergillus and *Fusarium* mycotoxin analysis on all cereal grains were performed at Trilogy Analytical Laboratories (Washinton, MO) using liquid chromatography-tandem mass spectroscopy. Ergot alkaloids were analyzed by refractive index high-performance liquid chromatography using Phenomenex Strata-X-CW (Phenomenex, Inc.) weak cation exchange and reversed phase column.

Physical Characteristics

Ingredient samples were analyzed for bulk density following the procedure by [Cromwell et al. \(2000\)](#) by pouring each ingredient into a tared 250-mL beaker, leveling off the top, and recording the weight of the tared beaker. Particle size of ingredients was analyzed with a Ro-Tap Sieve Shaker with 13 sieves of sieve opening sizes 53 to

3,360 µm (procedure S319.4, [ANSI/ASAE, 2008](#)). Ingredients were analyzed for swelling capacity based on the bed volume technique described by [Kuniak and Marchessault \(1972\)](#) and [Canibe and Bach Knudsen \(2002\)](#). Viscosity of ingredient samples was measured using a procedure modified after [Serena et al. \(2008\)](#) and was expressed in mPa · s. Briefly, 2 g of sample was dissolved in 10 mL of 0.9% NaCl and 0.02% NaN₃ solution and extracted in a water bath at 40 °C for 1 h. The sample was then centrifuged at 3,500 × g for 25 min at 23 °C and 0.5 mL of the supernatant was removed by suction. Viscosity of the supernatant was measured using a Brookfield LV-DV-2T viscometer (Brookfield Eng. Lab. Inc., Middleboro, MA) with a Wells-Brookfield Cone/Plate extension and a CPA-40Z cone spindle over a range of shear rates from 30.00 to 52.50 s⁻¹. Viscosity of solutions was measured at room temperature (23 °C). Water-binding capacity was analyzed in all ingredient samples following a modified procedure described by [Robertson et al. \(2000\)](#). In short, 3 g of sample was hydrated in 30 mL of 0.9% NaCl and 0.02% NaN₃ solution for 18 h at room temperature, and then centrifuged for 20 min at 3,000 × g. The sample was weighed after the supernatant had been removed, and values for water-binding capacity were recorded as g of water retained by the pellet (g/g of dry weight).

Calculations and Statistical Analysis

Apparent ileal digestibility (AID) values of AA in each diet were calculated using equation [1]:

$$\text{AID}_{\text{AA}, \%} = 100 - \left[\left(\frac{\text{AA}_{\text{digesta}}}{\text{AA}_{\text{feed}}} \right) \times \left(\frac{\text{Cr}_{\text{feed}}}{\text{Cr}_{\text{digesta}}} \right) \right] \times 100 \quad (1)$$

where AID_{AA} is the AID of an AA (%), AA_{digesta} is the concentration of that AA in the ileal digesta DM, AA_{feed} is the AA concentration of that AA in the feed DM, Cr_{feed} is the chromium concentration in the feed DM, and Cr_{digesta} is the chromium concentration in the ileal digesta DM. The AID of CP and starch were also calculated using this equation.

The basal endogenous flow to the distal ileum of each AA was determined based on the flow obtained after feeding the N-free diet using equation [2] ([Stein et al., 2007](#)):

$$\text{IAA}_{\text{end}} = \left[\text{AA}_{\text{digesta}} \times \left(\frac{\text{Cr}_{\text{feed}}}{\text{Cr}_{\text{digesta}}} \right) \right] \quad (2)$$

where IAA_{end} is the basal ileal endogenous loss of an AA (mg per kg DM intake). The basal ileal

endogenous loss of CP was determined using the same equation.

By correcting the AID for the IAA_{end} of each AA, standardized ileal digestibility (SID) values of AA were calculated using equation [3] (Stein et al., 2007):

$$SID_{AA} = \left[\frac{AID + IAA_{end}}{AA_{feed}} \right] \quad (3)$$

where SID_{AA} is the SID value (%) of each AA. The SID for CP was calculated using the same equation. The concentrations of standardized ileal digestible CP and AA were calculated by multiplying the SID value (%) by the CP and AA content of each cereal grain.

Data were analyzed using the MIXED procedure of SAS (SAS Institute Inc., Cary, NC). Outliers were detected using the ROBUSTREG procedure. An outlier was defined as a value with a standardized robust residual of greater than 3 or less than -3. The statistical model included source of grain as fixed effect and period and animal as random effects. Least squares means were estimated and separated using the PDIF statement in PROC MIXED. The pig was the experimental unit for all analyses. Results were considered significant at $P \leq 0.05$ and considered a trend at $P \leq 0.10$.

RESULTS

All pigs recovered from surgery without complications, and generally consumed their diets throughout the experiment without apparent problems. Two samples were excluded from all analyses due to statistical outliers being detected. Therefore, there were only six observations for the Brasetto rye diet and for the corn diet.

The GE among all grain samples ranged from 3,763 kcal/kg in Bono rye to 3,874 kcal/kg in corn (Table 3). The CP was numerically lowest in corn with 7.20%, followed by rye with values of 8.65%, 9.08%, and 8.90% for Bono, Daniello, and Brasetto rye, respectively. The CP of barley and wheat was 10.54% and 11.35%, respectively. The starch content was highest in corn (63.22%) and lowest in Brasetto rye (54.99%). The analyzed values for Lys were 0.36% in the three hybrid ryes, 0.39% in barley, 0.37% in wheat, and 0.27% in corn. The Met content was 0.15% in the three hybrid ryes and corn, and slightly greater in wheat and barley. Corn had the lowest Thr content of 0.27%, followed by Bono and Brasetto rye (0.29%), Daniello rye (0.30%), barley (0.33%), and wheat (0.35%). The Trp content was

also lowest in corn, followed by Bono rye, Daniello rye, Brasetto rye, wheat, and barley.

All cereal grains had low concentrations of free monosaccharides with glucose and sucrose being most abundant (Table 4). Rye had the greatest amount of hydrolyzed arabinose and xylose, ranging from 25.44 to 28.21 mg per g and 52.72 to 56.93 mg per g, respectively. Rye had greater β -glucan concentration than wheat and corn, but barley contained more β -glucan (4.36%) than all other grains. Rye had greater concentrations of fructans than barley, wheat, and corn. All ingredient samples had undetectable concentrations of *Aspergillus* and *Fusarium* mycotoxins, with the exception of Brasetto rye, wheat, and corn, which had 1.3, 6.1, and 0.7 mg per kg of deoxynivalenone, respectively (Table 5). The three hybrids of rye had small, but detectable, amounts of ergot alkaloids, ranging from 10.3 to 444.3 μ g per kg.

All ingredients were ground using the same hammer mill, thus, bulk density and particle size were not different among ingredients (Table 6). The mean particle size ranged from 213.3 to 383.0 μ m. The viscosity in the rye hybrids was numerically higher than in barley, wheat, and corn, and the water-binding capacity ranged from 0.87 g in Brasetto rye to 1.39 g of water per g dry weight in barley.

The AID of CP was least ($P < 0.001$) for Bono rye at 57.91%, and greatest in wheat at 75.70% (Table 7). The AID of starch ranged from 94.99% in Brasetto rye to 98.39% in corn. The AID of CP, starch, Arg, His, Lys, Phe, Ala, Cys, Glu, Pro, Ser, and Tyr did not differ among the three varieties of hybrid rye, but the AID of Ile, Met, Thr, Trp, Asp, Gly, and total AA was greater ($P < 0.05$) in Daniello rye than in Bono rye. The AID of Leu, Thr, and Asp was also greater in Daniello rye than in Brasetto rye ($P < 0.05$). For CP, starch, and most AA, the AID in barley, wheat, and corn were greater ($P < 0.05$) than in all three hybrid ryes. The AID of CP and most AA did not differ among barley, wheat, and corn, with the exception that the AID of Leu and Ala was greater ($P < 0.05$) in corn than in barley and wheat, the AID of Met was greater ($P < 0.05$) in wheat and corn than in barley, the AID of Cys was greater ($P < 0.05$) in barley and wheat than in corn, and the AID of Glu and Gly was greater ($P < 0.05$) in wheat than in barley and corn. The AID of Trp did not differ between barley and corn, nor did it differ between barley and wheat, but the AID of Trp was greater ($P < 0.05$) in wheat than in corn.

Table 3. Analyzed nutrient composition of three sources of hybrid rye, barley, wheat, and corn, as-fed basis

Item	Rye Bono	Rye Daniello	Rye Brasetto	Barley	Wheat	Corn
GE, kcal/kg	3,763	3,797	3,772	3,829	3,867	3,874
DM, %	87.56	88.15	87.19	88.17	87.85	88.10
CP, %	8.65	9.08	8.90	10.54	11.35	7.20
Ash, %	1.48	1.55	1.46	1.34	1.76	1.21
AEE, ¹ %	1.75	1.58	1.72	1.76	3.75	2.54
ADF, %	2.46	2.84	2.52	1.33	2.84	2.03
NDF, %	13.99	15.05	13.99	10.20	11.21	8.76
ADL, %	0.64	0.76	0.61	0.18	0.82	0.27
Insoluble dietary fiber, %	13.30	14.70	13.10	9.50	10.60	10.00
Soluble dietary fiber, %	1.90	1.80	3.50	3.30	0.50	ND ²
Total dietary fiber, %	15.20	16.50	16.60	12.80	11.10	10.00
Total starch	56.21	55.19	54.99	59.72	60.49	63.22
Indispensable AA, %						
Arg	0.44	0.45	0.44	0.48	0.53	0.36
His	0.21	0.21	0.21	0.23	0.26	0.21
Ile	0.32	0.32	0.32	0.39	0.41	0.28
Leu	0.57	0.57	0.56	0.72	0.73	0.84
Lys	0.36	0.36	0.36	0.39	0.37	0.27
Met	0.15	0.15	0.15	0.17	0.18	0.15
Phe	0.42	0.44	0.42	0.56	0.50	0.37
Thr	0.29	0.30	0.29	0.35	0.33	0.27
Trp	0.08	0.09	0.10	0.12	0.11	0.06
Val	0.43	0.44	0.44	0.53	0.51	0.37
Total	3.27	3.33	3.29	3.94	3.93	3.18
Dispensable AA, %						
Ala	0.39	0.38	0.38	0.40	0.43	0.53
Asp	0.63	0.63	0.63	0.61	0.63	0.52
Cys	0.21	0.21	0.20	0.25	0.27	0.17
Glu	1.99	2.12	2.04	2.54	2.95	1.32
Gly	0.39	0.39	0.40	0.40	0.48	0.30
Pro	0.89	0.94	0.88	1.20	1.00	0.68
Ser	0.36	0.37	0.36	0.40	0.45	0.34
Tyr	0.20	0.20	0.19	0.27	0.26	0.23
Total	5.06	5.24	5.08	6.07	6.47	4.09
Total AA, %	8.52	8.75	8.57	10.21	10.60	7.41

¹AEE = acid-hydrolyzed ether extract.²ND = not detected.

The SID of CP was greater ($P < 0.05$) in barley, wheat, and corn than in the three hybrids of rye (Table 8). The SID of CP and all AA did not differ between Bono rye and Brasetto rye. The SID of Ile, Met, Thr, and Asp was greater ($P < 0.05$) in Daniello rye than in Bono rye, and the SID of Lys, Thr, Val, and Asp was greater ($P < 0.05$) in Daniello rye than in Brasetto rye. The SID of CP and all AA except Pro was greater ($P < 0.05$) in barley, wheat, and corn than in the three hybrid ryes. The SID of CP and most AA did not differ among barley, wheat, and corn, with the exception that the SID of Arg, Leu, Met, and Asp was greater ($P < 0.05$) in corn than in barley, the SID of Ala was greater ($P < 0.05$) in corn than in barley and wheat, and the SID of

Gly was greater ($P < 0.05$) in wheat than in barley and corn.

The concentration of standardized ileal digestible CP was greatest ($P < 0.001$) in wheat, followed by barley, Daniello rye, Brasetto rye, Bono rye, and corn (Table 9). The concentration of standardized ileal digestible Lys did not differ between barley and wheat, but was greater ($P < 0.001$) in Daniello rye than in corn. The concentration of standardized ileal digestible Met was greatest ($P < 0.001$) in wheat, followed by barley, but was greater ($P < 0.001$) in corn than in all three rye cultivars. Concentrations of standardized ileal digestible Thr and Trp were greatest ($P < 0.001$) in barley, followed by wheat. There was no difference between Daniello rye and corn for concentration of standardized ileal

Table 4. Analyzed carbohydrate composition in three sources of hybrid rye, barley, wheat, and corn, DM basis¹

Item	Rye Bono	Rye Daniello	Rye Brasetto	Barley	Wheat	Corn
Free sugars, µg per g						
Fucose	12.7	14.4	15.0	0.0	0.0	0.0
Arabinose	53.0	69.2	75.9	38.4	59.3	25.6
Galactose	63.4	51.0	70.8	122.5	82.0	84.9
Glucose	2,674.8	2,508.2	1,676.5	1,132.6	1,561.0	3,480.5
Xylose	310.2	360.3	300.4	164.7	217.4	179.5
Mannose	49.4	0.0	43.6	39.8	47.0	0.0
Fructose	912.7	725.2	1002.6	841.6	539.1	1,546.9
Hydrolyzed sugars, mg per g						
Arabinose	26.2	28.2	25.4	9.1	17.8	10.0
Galactose	10.9	10.7	10.3	7.8	11.2	10.1
Glucose	786.7	787.4	781.7	833.2	764.9	848.0
Xylose	52.7	56.2	56.9	24.0	44.6	23.6
Arabinose:Xylose	0.5	0.5	0.5	0.4	0.4	0.4
β-glucans, %	2.0	2.1	2.1	4.4	0.8	0.2
Fructans, ² %	1.2	1.2	1.0	0.4	0.2	0.1
Sucrose, %	1.2	1.5	1.3	0.8	0.8	0.9

¹Total galacturonic and glucuronic acid in all ingredients were analyzed, but not detected.

²Fructan content was determined by inulin analysis.

Table 5. Mycotoxin content of three sources of hybrid rye, barley, wheat, and corn, DM basis

Toxin	Rye Bono	Rye Daniello	Rye Brasetto	Barley	Wheat	Corn
<i>Aspergillus</i>						
Aflatoxin B1, µg per kg	<5	<5	<5	<5	<5	<5
Aflatoxin B2, µg per kg	<5	<5	<5	<5	<5	<5
Aflatoxin G1, µg per kg	<5	<5	<5	<5	<5	<5
Aflatoxin G2, µg per kg	<5	<5	<5	<5	<5	<5
<i>Fusarium</i>						
Deoxynivalenol, mg per kg	<0.1	<0.1	1.3	<0.1	6.1	0.7
3-Acetyl DON, ¹ mg per kg	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
15-Acetyl DON, ¹ mg per kg	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
T-2, mg per kg	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Zearalenone, mg per kg	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Ergot, µg per kg	444.3	10.4	10.3	—	—	—

¹DON = deoxynivalenol.

digestible Thr, but both Daniello rye and Brasetto rye had a greater ($P < 0.001$) concentration of standardized ileal digestible Trp than corn.

DISCUSSION

Although rye has historically not been used extensively in animal feeding, hybrid rye has the potential to be cost-effective in comparison with other cereal grains when used in diets for pigs. Hybrid rye has several agronomic advantages over other small cereal grains and older rye cultivars, including superior drought tolerance, overwintering ability, and increased yield (Jurgens et al., 2012; Schittenhelm et al., 2013). In addition, current

varieties of hybrid rye have reduced incidence of ergot (Miedaner and Geiger, 2015), which mitigates some of the risk previously associated with including rye in swine diets. In the United States, rye is considered “ergoty” if it contains more than 0.3% ergot by weight (USDA, 2013), at which point the value may be reduced. In the present study, the concentration of ergot in the three hybrid ryes were well below this threshold. Another perceived limitation for including rye in swine diets is the prevalence of pentoses, which are considered to have antinutritional properties (Antonioni et al., 1981). In the present study, rye contained more hydrolyzed xylose and arabinose compared with barley, wheat, and corn. Xylose is the only sugar

Table 6. Physical characteristics of three sources of hybrid rye, barley, wheat, and corn, as-fed basis unless otherwise noted

Item	Rye Bono	Rye Daniello	Rye Brasetto	Barley	Wheat	Corn
Bulk density, g/L	615.4	620.5	614.5	653.1	597.8	579.9
Particle size, μm	287.7	351.1	383.0	373.4	213.3	237.0
Swelling, mL/g dry weight	3.82	3.21	3.44	3.49	2.94	2.75
Viscosity, mPa · s	2.17	2.34	2.48	1.48	1.18	1.54
WBC, ¹ g water/g dry weight	1.19	1.11	0.87	1.39	1.06	1.12

¹WBC = water-binding capacity.**Table 7.** Apparent ileal digestibility (%) of CP, starch, and AA in three sources of hybrid rye, barley, wheat, and corn

Item	Rye Bono	Rye Daniello	Rye Brasetto	Barley	Wheat	Corn	SEM	P value
CP	57.9 ^d	62.8 ^{cd}	59.3 ^d	72.2 ^a	75.7 ^{ab}	67.4 ^{bc}	2.20	<0.001
Starch	95.1 ^b	95.4 ^b	95.0 ^b	95.8 ^b	97.6 ^a	98.4 ^a	0.49	<0.001
Indispensable AA								
Arg	67.1 ^c	72.0 ^b	70.2 ^{bc}	79.7 ^a	83.7 ^a	81.9 ^a	1.95	<0.001
His	67.4 ^b	67.9 ^b	66.6 ^b	79.0 ^a	82.7 ^a	81.0 ^a	1.77	<0.001
Ile	60.0 ^c	66.0 ^b	64.2 ^{bc}	75.6 ^a	78.3 ^a	74.9 ^a	1.67	<0.001
Leu	65.3 ^{cd}	69.3 ^c	64.0 ^d	78.7 ^b	81.1 ^b	86.0 ^a	1.67	<0.001
Lys	52.1 ^b	57.6 ^b	51.2 ^b	68.6 ^a	69.7 ^a	64.4 ^a	2.59	<0.001
Met	69.8 ^d	73.2 ^c	72.2 ^{cd}	80.2 ^b	84.2 ^a	84.3 ^a	1.29	<0.001
Phe	69.5 ^b	72.7 ^b	69.4 ^b	81.3 ^a	82.5 ^a	81.0 ^a	1.51	<0.001
Thr	44.9 ^c	52.0 ^b	43.7 ^c	65.3 ^a	63.5 ^a	61.3 ^a	2.39	<0.001
Trp	58.9 ^d	66.7 ^c	66.4 ^c	78.9 ^{ab}	81.4 ^a	74.0 ^b	2.49	<0.001
Val	56.3 ^{bc}	61.2 ^b	54.5 ^c	72.7 ^a	70.1 ^a	68.2 ^a	2.06	<0.001
Total	61.3 ^b	65.7 ^b	61.5 ^b	76.3 ^a	77.6 ^a	77.4 ^a	1.87	<0.001
Dispensable AA								
Ala	50.2 ^c	54.4 ^c	51.3 ^c	65.0 ^b	64.8 ^b	78.6 ^a	2.39	<0.001
Asp	57.9 ^c	62.6 ^b	55.9 ^c	68.1 ^a	70.2 ^a	71.5 ^a	2.14	<0.001
Cys	63.9 ^c	66.4 ^c	66.2 ^c	79.8 ^a	79.7 ^a	71.3 ^b	1.43	<0.001
Glu	81.1 ^d	83.0 ^{cd}	81.2 ^d	86.4 ^b	91.7 ^a	84.7 ^{bc}	1.09	<0.001
Gly	30.0 ^d	42.0 ^c	37.0 ^{cd}	55.8 ^b	65.2 ^a	51.1 ^b	4.65	<0.001
Ser	60.7 ^b	65.1 ^b	60.7 ^b	74.2 ^a	77.9 ^a	74.4 ^a	1.94	<0.001
Tyr	60.2 ^b	61.8 ^b	60.4 ^b	76.4 ^a	77.7 ^a	74.9 ^a	1.0	<0.001
Total	68.3 ^d	72.2 ^c	70.5 ^{cd}	78.2 ^b	84.2 ^a	73.4 ^c	2.07	<0.001
Total AA, %	64.7 ^d	68.9 ^c	65.8 ^{cd}	77.3 ^{ab}	80.9 ^a	75.3 ^b	1.92	<0.001

in the backbone of arabinoxylans, and arabinose is the main sugar in the side chains. Arabinoxylans are the main constituent of fiber in cereal grains and are indigestible by endogenous enzymes in monogastric animals. However, arabinoxylans will be partially fermented in the large intestine with a subsequent synthesis and absorption of short-chained fatty acids, which will contribute energy to the pig. Likewise, fermentation in the hindgut will also increase the synthesis of butyrate by intestinal microbes and improve intestinal health (Bach Knudsen et al., 2005, 2016, 2017).

The concentration of starch in the hybrid rye was in agreement with values reported by Strang et al. (2016) and Cervantes-Pahm et al. (2014), but the AID of starch in hybrid rye obtained in this

experiment was greater than values reported by Lærke (2015) and Cervantes-Pahm et al. (2014). The reason for the relatively high AID of starch in all grains in this experiment may be that the particle size was low, which increases the AID of starch (Rojas and Stein, 2015).

The CP and AA concentrations in the three hybrids of rye used in the experiment were lower than values in summarized feed tables from NRC (2012) as well as several other published reports (Brestensky et al., 2013; Cervantes-Pahm et al., 2014; Rodehutscord et al., 2016). However, concentrations of most AA in the rye used in the present experiment were in agreement with values by Strang et al. (2016) and by Evonik Industries (2016). The sample size reported by NRC for CP and AA in

Table 8. Standardized ileal digestibility (%) of CP and AA in three sources of hybrid rye, barley, wheat, and corn¹

Item	Rye Bono	Rye Daniello	Rye Brasetto	Barley	Wheat	Corn	SEM	P value
CP	75.2 ^b	79.7 ^b	76.4 ^b	87.1 ^a	89.5 ^a	89.2 ^a	2.20	<0.001
Indispensable AA								
Arg	79.3 ^c	83.3 ^c	82.1 ^c	90.4 ^b	93.4 ^{ab}	97.2 ^a	1.95	<0.001
His	75.6 ^b	76.2 ^b	74.8 ^b	86.2 ^a	89.4 ^a	88.8 ^a	1.77	<0.001
Ile	71.7 ^c	76.1 ^b	74.5 ^{bc}	84.1 ^a	86.9 ^a	87.4 ^a	1.67	<0.001
Leu	74.2 ^c	77.2 ^c	73.1 ^c	85.8 ^b	88.2 ^{ab}	92.2 ^a	1.67	<0.001
Lys	62.1 ^{bc}	67.4 ^b	60.9 ^c	77.3 ^a	79.3 ^a	78.4 ^a	2.69	<0.001
Met	76.4 ^d	79.4 ^c	78.3 ^{cd}	85.6 ^b	89.3 ^a	90.9 ^a	1.29	<0.001
Phe	77.4 ^b	80.2 ^b	77.2 ^b	87.1 ^a	89.0 ^a	90.0 ^a	1.51	<0.001
Thr	64.0 ^c	70.6 ^b	62.8 ^c	81.0 ^a	80.4 ^a	82.1 ^a	2.32	<0.001
Trp	71.6 ^c	79.5 ^b	76.2 ^{bc}	87.8 ^a	89.6 ^a	88.9 ^a	2.49	<0.001
Val	69.9 ^{bc}	74.3 ^{bc}	68.1 ^c	83.7 ^a	81.6 ^a	84.8 ^a	2.06	<0.001
Total	72.4 ^b	76.5 ^b	72.4 ^b	85.3 ^a	86.7 ^a	89.0 ^a	1.87	<0.001
Dispensable AA								
Ala	65.6 ^c	70.0 ^c	67.2 ^c	79.8 ^b	79.2 ^b	90.0 ^a	2.39	<0.001
Asp	68.8 ^d	73.2 ^c	66.8 ^d	78.9 ^b	81.0 ^{ab}	85.0 ^a	2.14	<0.001
Cys	73.6 ^b	76.1 ^b	75.8 ^b	87.4 ^a	87.3 ^a	83.8 ^a	1.43	<0.001
Glu	85.6 ^c	87.3 ^c	85.7 ^c	90.0 ^b	94.9 ^a	91.7 ^b	1.09	<0.001
Gly	67.5 ^c	77.8 ^b	74.5 ^{bc}	90.8 ^a	96.4 ^a	91.7 ^a	4.65	<0.001
Ser	74.3 ^b	78.5 ^b	74.4 ^b	86.2 ^a	88.5 ^a	89.1 ^a	1.94	<0.001
Tyr	73.1 ^b	74.8 ^b	73.3 ^b	85.4 ^a	87.1 ^a	86.6 ^a	1.30	<0.001
Total	87.4 ^c	90.8 ^{bc}	89.9 ^{bc}	93.9 ^b	99.1 ^a	99.3 ^a	2.07	<0.001
Total AA	80.6 ^b	84.2 ^b	81.7 ^b	90.3 ^a	93.5 ^a	94.1 ^a	1.88	<0.001

¹Values for standardized ileal digestibility were calculated by correcting the values for apparent ileal digestibility for basal ileal endogenous losses. Basal endogenous losses were determined (g/kg of DM) as CP, 16.39; Arg, 0.55; His, 0.55; Iso, 0.18; Leu, 0.35; Lys, 0.54; Met, 0.36; Phe, 0.10; Thr, 0.35; Trp, 0.58; Val, 0.10; Ala, 0.62; Asp, 0.63; Cys, 0.70; Glu, 0.20; Gly, 0.96; Pro, 1.53; Ser, 5.15; and Tyr, 0.50.

rye was small ($n = 2$), and there is often variation among cereal grain genotypes in concentrations of CP and AA (Strang et al., 2016; Zuber et al., 2016). This is particularly true when comparing old cultivars with new cultivars (Peltonen-Sainio et al., 2012), which may explain some of the discrepancies among published values.

The calculated SID of CP and AA in the three hybrids of rye used in the present experiment was also comparable to Strang et al. (2016) and Cervantes-Pahm et al. (2014), but was greater than values reported by Brestensky et al. (2013), and less than values from NRC (2012) and Evonik Industries (2016). Nevertheless, the concentrations of standardized ileal digestible Lys, Met, Thr, and Trp were in close agreement with Strang et al. (2016) and Evonik Industries (2016), but less than values reported by Cervantes-Pahm et al. (2014), Brestensky et al. (2013), and NRC (2012).

The concentrations of CP and AA in barley, wheat, and corn were comparable to previous data (NRC, 2012; Cervantes-Pahm et al., 2014; Stein et al., 2016). The SID of CP and AA in barley and corn was slightly greater in the present study than reported by NRC (2012), Cervantes-Pahm et al. (2014), and Stein

et al. (2016), but the SID of CP and AA in wheat was comparable to values from Stein et al. (2016).

The reduced SID of CP and AA in rye compared with barley, wheat, and corn may be due to the greater concentration of fructans and total dietary fiber in rye. The observation that the three hybrid rye cultivars contained more fructans than barley, wheat, and corn, and more arabinose, xylose, and beta-glucans than wheat and corn is in agreement with previous data (Rodehutsord et al., 2016). The values obtained for fructans and total dietary fiber in the present study vary slightly from Rodehutsord; however, the values obtained for rye are close to what was recently published by Strang et al. (2016). Greater concentrations of fructans and soluble dietary fiber have been associated with increased viscosity and reduced nutrient digestibility, particularly in poultry (Annison, 1991; Choct and Annison, 1992). Due to disparate shear rates and shear stresses used to measure viscosity of digesta samples, comparing numeric values for viscosity among laboratories is not possible (Dikeman and Fahey, 2006). However, the increased viscosity of rye than in barley, wheat, and corn that was observed in this experiment has also been previously

Table 9. Concentrations (g/kg) of standardized ileal digestible CP and AA in three sources of hybrid rye, barley, wheat, and corn¹

Item	Rye Bono	Rye Daniello	Rye Brassetto	Barley	Wheat	Corn	SEM	P value
CP	65.1 ^d	72.4 ^c	68.0 ^{cd}	91.8 ^b	101.7 ^a	64.3 ^d	2.018	<0.001
Indispensable AA								
Arg	3.5 ^d	3.8 ^c	0.3.6 ^{cd}	4.3 ^b	5.0 ^a	3.5 ^d	0.083	<0.001
His	1.6 ^d	1.6 ^d	1.6 ^d	2.0 ^b	2.3 ^a	1.9 ^c	0.042	<0.001
Ile	2.3 ^d	2.4 ^c	2.4 ^{cd}	3.3 ^b	3.6 ^a	2.5 ^c	0.057	<0.001
Leu	4.2 ^c	4.4 ^c	4.1 ^c	6.2 ^b	6.4 ^b	7.7 ^a	0.105	<0.001
Lys	2.2 ^{bc}	2.4 ^b	2.2 ^{bc}	3.0 ^a	2.9 ^a	2.1 ^c	0.094	<0.001
Met	1.1 ^d	1.2 ^d	1.2 ^d	1.4 ^b	1.6 ^a	1.4 ^c	0.024	<0.001
Phe	3.3 ^d	3.5 ^c	3.2 ^d	4.9 ^a	4.5 ^b	3.3 ^d	0.068	<0.001
Thr	1.9 ^d	2.1 ^c	1.8 ^d	2.8 ^a	2.6 ^b	2.2 ^c	0.071	<0.001
Trp	0.6 ^d	0.7 ^c	0.7 ^c	1.0 ^a	1.0 ^b	0.5 ^d	0.027	<0.001
Val	3.0 ^d	3.3 ^c	3.0 ^d	4.4 ^a	4.2 ^b	3.1 ^d	0.095	<0.001
Total	23.7 ^d	25.5 ^c	23.8 ^d	33.6 ^a	34.1 ^a	28.3 ^b	0.634	<0.001
Dispensable AA								
Ala	2.6 ^d	2.6 ^d	2.6 ^d	3.2 ^c	3.4 ^b	4.8 ^a	0.097	<0.001
Asp	4.3 ^d	4.6 ^{bc}	4.2 ^d	4.8 ^{ab}	5.1 ^a	4.4 ^{cd}	0.134	<0.001
Cys	1.5 ^c	1.6 ^c	1.5 ^c	2.2 ^b	2.4 ^a	1.4 ^d	0.035	<0.001
Glu	17.0 ^d	18.5 ^c	17.5 ^d	22.8 ^b	28.0 ^a	12.1 ^e	0.227	<0.001
Gly	2.6 ^d	3.0 ^c	3.0 ^d	3.7 ^b	4.6 ^a	3.0 ^c	0.178	<0.001
Ser	2.7 ^d	2.9 ^c	2.7 ^d	3.5 ^b	4.0 ^a	3.1 ^c	0.073	<0.001
Tyr	1.5 ^c	1.5 ^c	1.4 ^c	2.3 ^a	2.3 ^a	2.0 ^b	0.029	<0.001
Total	44.2 ^d	47.6 ^c	45.7 ^{cd}	57.0 ^b	64.1 ^a	40.6 ^e	1.055	<0.001
Total AA	68.6 ^d	73.7 ^c	70.0 ^{cd}	92.2 ^b	99.2 ^a	69.7 ^d	1.695	<0.001

¹Concentrations of standardized ileal digestible CP and AA were calculated by multiplying values for the standardized ileal digestibility (%) of CP and AA by the concentration of CP and AA in each cereal grain.

reported (Lázaro, 2003; Rodehutsord, 2016). It is possible that the combination of increased concentrations of fructans and nonstarch polysaccharides in rye is the reason for the reduced SID of AA in rye compared with barley, wheat, and corn.

In conclusion, the AID and SID of most AA in hybrid rye were less than in barley, wheat, and corn, but concentrations of standardized ileal digestible CP and most AA in hybrid rye was greater than or comparable to concentrations in corn. Thus, the hybrid rye used in this experiment may replace corn in diets for pigs without changing the provision of digestible AA. Further research is warranted to determine the digestibility of energy and other nutrients and the appropriate inclusion rate of hybrid rye in diets for pigs at various stages of production.

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