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Non Ruminant Nutrition

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High inclusion rates of hybrid rye instead of corn in diets for growing-finishing pigs do not influence the overall growth performance and most carcass traits are not influenced by hybrid rye

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Abstract

It was hypothesized that hybrid rye may replace corn in diets for growing and finishing pigs without impacting growth performance, carcass characteristics, or meat quality. A total of 128 pigs (23.69 ± 2.51 kg) were allotted to four treatments with eight replicate pens per treatment. Phases 1 and 2 diets were fed for 35 d each and phase 3 diets were fed for 27 d. Within each phase, pigs were fed a control corn and soybean meal diet or a diet in which 33%, 66%, or 100% of the corn in the control diet was replaced with hybrid rye. Average daily gain (**ADG**) and average daily feed intake (**ADFI**) decreased (linear, $P < 0.05$) in phase 1 with increased dietary inclusion of hybrid rye. In phase 3, gain:feed (**G:F**) increased and then decreased (quadratic, $P < 0.05$) with more hybrid rye in the diet. Overall ADG, ADFI, and G:F did not differ among treatments. Diet did not impact most carcass traits, but loin (visual) and backfat (instrumental L^*) color were paler (linear, $P < 0.05$) with greater inclusion of hybrid rye in the diet. Organ weights increased (linear, $P < 0.05$) with increased dietary hybrid rye. In conclusion, pigs fed hybrid rye consumed less feed in phase 1, resulting in reduced ADG, but growth performance for the entire growing-finishing period did not differ among treatments. Hybrid rye may replace all the corn in growing and finishing pig diets without diminishing growth performance or carcass quality, but feed intake may be reduced at high inclusion rates.

Key words: carcass traits, corn, finishing pigs, growing pigs, hybrid rye

Introduction

Hybrid rye may replace a portion of barley in diets for growing and finishing pigs with minimal impact on growth performance or carcass characteristics (Schwarz et al., 2015; Bussières, 2018). Hybrid rye may also substitute wheat in growing pig diets at high inclusion rates without negative effects on growth performance, but at very high inclusion rates in finishing diets, feed intake may be reduced if hybrid rye replaces wheat (Smit et al., 2019). Growing pigs fed diets containing increasing levels of hybrid rye at the expense of corn for 27 d had final body weight, average daily gain (**ADG**), and gain:feed (**G:F**) that were not different from that of pigs fed a control diet based on corn and soybean meal (McGhee and Stein, 2021). However, a tendency for reduced average daily feed intake (**ADFI**) as hybrid rye increased in the diet was observed. In a two-way choice preference test, pigs

Abbreviations

ADG	average daily gain
ADFI	average daily feed intake
G:F	gain to feed ratio

preferred diets containing corn to diets containing hybrid rye, and, therefore, reduced feed intake may be expected if hybrid rye is fed in large quantities to pigs because of its taste, smell, or physical behavior in the gastrointestinal tract. To our knowledge, effects of replacing corn by hybrid rye throughout the growing-finishing period have not been reported and no data for carcass characteristics of pigs fed hybrid rye instead of corn are available. Therefore, an experiment was conducted to test the hypothesis that ADG and carcass characteristics will not be affected if hybrid rye partially replaces corn in diets for growing-finishing pigs. It was also hypothesized that reduced ADFI, and consequently ADG, will be observed if hybrid rye replaces 100% of the corn in diets for growing and finishing pigs.

Materials and Methods

The protocol for the experiment was approved by the Institutional Animal Care and Use Committee at the University of Illinois, Urbana, IL, USA (protocol number: 19130). A total of 128 growing pigs that were the offspring of Line 359 boars and Camborough sows (Pig Improvement Company, Henderson, TN, USA) with an initial body weight of 23.69 ± 2.51 kg were allotted to a completely randomized design with four treatment groups. Thirty-two pens were used with four pigs per pen (two gilts and two barrows) and eight replicate pens per treatment group. Pigs were housed in an environmentally controlled barn with partially slatted floors, a nipple waterer, and a stainless steel feeder. Pens measured 1.83 × 2.59 m, which resulted in a floor space of 1.18 m^2 for each pig. Water and feed were available to the pigs on an ad libitum basis. All diets were fed in mash form.

Diets were fed in three phases with phase 1 diets being fed for 35 d (grower phase), phase 2 diets for 35 d (early finisher phase), and phase 3 diets for 27 d (late finisher phase). For each phase, a control diet primarily based on corn and soybean meal was formulated. Three additional diets were formulated for each phase by replacing 33%, 66%, or 100% of the corn in the control diet with hybrid rye (Table 1). Both corn and hybrid rye were ground to a mean particle size of approximately 550 microns. The hybrid rye was sourced from a feed mill in Lexington, KY, USA, and was grown in 2020, and the corn was grown locally. All diets were formulated to meet or exceed the estimated requirements for standardized ileal digestible amino acids, vitamins, and minerals for 25 to 60, 60 to 90, or 90 to 125 kg pigs (NRC, 2012). Diets were formulated based on determined values for metabolizable energy, standardized ileal digestible amino acids, and standardized total tract digestible P in hybrid rye (McGhee and Stein, 2018, 2019, 2020), and values for corn and soybean meal were according to NRC (2012). Diets within each phase were identical in standardized ileal digestible amino acids and standardized total tract digestible P, but diets were not formulated to be isocaloric or isonitrogenous; therefore, as hybrid rye inclusion increased, the concentration of total dietary fiber and crude protein increased, whereas the calculated concentration of metabolizable energy decreased.

Individual pig weights were recorded at the beginning of the experiment and at the conclusion of each phase. Feed in the feeders was checked daily. Feed allowance was recorded daily and feed left in the feeders at the end of each phase was weighed

Table 1. Ingredient composition (as-is basis) of experimental diets with increasing replacement of corn with hybrid rye[1]

	Phase 1: Grower (day 1 to 35)[2]				Phase 2: Early finisher (day 35 to 70)[2]				Phase 3: Late finisher (day 70 to 97)[2]			
Ingredient, %	0%	33%	66%	100%	0%	33%	66%	100%	0%	33%	66%	100%
Corn	67.37	45.14	22.25	—	79.37	53.22	26.22	—	82.68	57.18	25.56	—
Hybrid rye	—	22.24	45.16	67.45	—	26.21	53.25	79.50	—	25.54	57.22	82.81
Soybean meal	27.00	27.00	27.00	27.00	15.00	15.00	15.00	15.00	12.00	12.00	12.00	12.00
Soybean oil	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
Limestone	0.85	0.89	0.94	0.99	0.75	0.80	0.87	0.95	0.71	0.77	0.84	0.91
Dicalcium phosphate	1.00	0.94	0.86	0.77	0.88	0.77	0.66	0.55	0.72	0.62	0.50	0.39
L-Lysine HCl, 78%	0.19	0.18	0.17	0.15	0.32	0.31	0.30	0.28	0.26	0.25	0.23	0.22
DL-Methionine, 98%	0.02	0.03	0.04	0.05	0.02	0.03	0.04	0.05	—	0.01	0.02	0.03
L-Threonine, 98%	0.02	0.03	0.03	0.04	0.09	0.10	0.10	0.11	0.07	0.07	0.08	0.09
Salt	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Vitamin–mineral premix[3]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

[1]Calculated values: grower diets: 18% to 20% crude protein and 1.12% to 1.16% total Lys; early finisher diets: 13% to 15% crude protein and 0.89% to 0.95% total Lys; late finisher diets: 12% to 14% crude protein and 0.76% to 0.82% total Lys.

[2]The percentages indicate the amount of corn that was replaced with hybrid rye.

[3]The vitamin–micromineral premix provided the following quantities of vitamins and microminerals per kilogram of complete diet: vitamin A as retinyl acetate, 11,150 IU; vitamin D_3 as cholecalciferol, 2,210 IU; vitamin E as selenium yeast, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.42 mg; thiamin as thiamine mononitrate, 1.10 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 1.00 mg; vitamin B_{12}, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.6 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 125 mg as iron sulfate; I, 1.26 mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.30 mg as sodium selenite and selenium yeast; and Zn, 125.1 mg as zinc hydroxychloride.

to calculate pen feed disappearance. If a pig was removed from a pen during the experiment, individual pig weights and the weight of feed in the feeder at the time of removal were recorded.

At the conclusion of phase 3, one pig per pen (four gilts and four barrows from each treatment) was harvested at the Meat Science Laboratory at the University of Illinois. Feed was withheld from pigs for approximately 16 h before slaughter. Prior to selecting the pigs for slaughter, pens within treatment were randomly assigned to deliver either a gilt or a barrow for slaughter, and the pig with the assigned sex that had a body weight that was closest to the pen average was then identified. Immediately prior to slaughter, pigs were weighed to determine ending live weight. Head-to-heart electrical stunning was used to immobilize pigs before slaughter by exsanguination. Approximately 45 min postmortem, hot carcass weights were recorded. The weight of the liver, kidney, heart, and full and empty gastrointestinal tracts was also recorded. Carcasses were split down the midline and chilled for 24 h at 4 °C prior to loin quality evaluation on the left side of the carcass.

Loin quality was evaluated on the cut surface of the longissimus muscle between the 10th and 11th rib following oxygenation of myoglobin for approximately 20 min at 4 °C. Fat depth was measured between the 10th and 11th ribs at three-fourths distance of the longissimus thoracis muscle from the dorsal side of the vertebral column. Instrumental color on the longissimus muscle and fat (L^*, a^*, and b^*; CIE, 1978) was measured using a Minolta CR-400 Chroma meter (Minolta Camera Co., Ltd, Osaka, Japan) with a D65 light source and a 10° observer angle with an aperture size of 8 mm. Ultimate pH of the longissimus thoracis was measured using a handheld pH meter fitted with a Hanna glass electrode calibrated at 4 °C (REED SD-230 Series pH/ORP Datalogger, 0.00 to 14.00 ph/0-199 mV; Hanna FC200B electrode). Visual color and marbling scores (National Pork Producers Council, 1999) and subjective firmness scores (National Pork Producers Council, 1991) were determined by a single, trained technician. The loin eye area was measured by tracing the surface of the longissimus muscle on a double-matted acetate paper. Tracings were later measured twice using a digitizer tablet (Wacom, Vancouver, WA) and Adobe Photoshop CS6, and the average of the two measurements was recorded. Drip loss was measured according to Boler et al. (2011). Carcass yield (%) was calculated by dividing hot carcass weight by ending live weight and multiplied by 100. Fat-free lean (%) was calculated using the following equation (Lowell et al., 2018): [8.588 + (0.465 × hot carcass weight, lbs) – (21.896 × backfat thickness, in) + (3.005 × loin eye area, in^2)]/hot carcass weight, lbs) × 100.

Cook loss and Warner–Bratzler shear force were measured in loin chops at 63 and 71 °C final internal temperature. To measure cook loss and Warner–Bratzler shear force, loin chops were first thawed in packaging at 4 °C for approximately 24 h and weighed. Loin chops were cooked on Farberware Open Hearth grills (model 455N, Walter Kidde, Bronx, NY, USA). Internal temperature was monitored during cooking through copper-constantan thermocouples (Type T, Omega Engineering, Stamford, CT, USA) placed in the geometric center of each chop. The thermocouples were connected to a digital data logger (Omega HH378, Stamford, CT, USA). Chops were cooked to an internal temperature of 31 or 35°C, flipped, and then cooked until they reached an internal temperature of 63 or 71°C. Chops were then removed, allowed to cool to approximately 25°C, and final weight was recorded. Cook loss was expressed as a percentage of initial weight and calculated by subtracting cooked weight from initial weight and dividing by initial weight. To determine Warner–Bratzler shear force, four 1.25-cm diameter cores per chop were removed parallel to the orientation of the muscle fibers and sheared using a texture analyzer (model TA.HD Plus; Texture Technologies Corp., Scarsdale, NY/Stable Microsystems, Godalming, UK) with a blade speed of 3.33 mm per second and a load cell capacity of 100 kg. The mean shear force of the four cores for each loin chop was reported. Sensory characteristics were evaluated independently by six panelists trained to evaluate pork chops according to the Sensory Guidelines from the American Meat Science Association (AMSA, 2015). All chops were cooked to an internal temperature of 63 °C and scored for tenderness, juiciness, and flavor on a scale of 0 to 15, where 0 represented extremely tough, dry, or not flavorful, and 15 represented extremely tender, juicy, or flavorful.

Within each dietary phase, multiple 1-t batches of diets were mixed. Each batch of diet was subsampled, and at the end of the experiment, 1 kg diet samples from each batch were mixed within diet and phase, and a subsample of the mixed samples was finely ground with a coffee grinder and analyzed. Diet samples and a sample of hybrid rye were analyzed for dry matter (method 930.15; AOAC Int., 2007) and ash (method 942.05; AOAC Int., 2007). The gross energy in diets and in hybrid rye was measured using an isoperibol bomb calorimeter (model 6400, Parr Instruments, Moline, IL, USA) with benzoic acid used as the standard for calibration. Total starch was analyzed by the glucoamylase procedure (method 979.10; AOAC Int., 2007). Nitrogen (method 990.03; AOAC Int., 2007) was measured using a Leco Nitrogen Determinator (model FP628, Leco Corp., St. Joseph, MI, USA), and crude protein was calculated as 6.25 × N. Diets and hybrid rye were analyzed for insoluble dietary fiber and soluble dietary fiber on an Ankom Total Dietary Fiber Analyzer (Ankom Technology, Macedon, NY, USA) using method 991.43 (AOAC Int., 2007), and total dietary fiber was calculated as the sum of insoluble and soluble dietary fiber. Acid-hydrolyzed ether extract was measured by crude fat extraction using petroleum ether ($Ankom^{XT15}$, Ankom Technology, Macedon, NY, USA) following hydrolysis using 3N HCl ($Ankom^{HCl}$, Ankom Technology, Macedon, NY, USA). Ether extract was determined in diets and hybrid rye (method 920.39 [A]; AOAC Int., 2007), and concentration of fatty acids was determined by method 996.06 (AOAC Int., 2007) following extraction of methyl esters (method Ce 2-66; AOCS, 1998). Samples of diets and hybrid rye were analyzed for amino acids on a Hitachi Amino Acid Analyzer, Model No. L8800 (Hitachi High Technologies America, Inc., Pleasanton, CA, USA) using ninhydrin for post-column derivatization and norleucine as the internal standard (method 982.30 E[a, b, c]; AOAC Int., 2007). The concentration of ergot alkaloids in hybrid rye was analyzed by North Dakota State University Veterinary Diagnostic Laboratory (Fargo, ND, USA) using liquid chromatography-tandem mass spectrometry.

Data were summarized for each treatment group. ADG, ADFI, and G:F were calculated. One pig was removed from the experiment due to leg injury in phase 1, and feed intake and G:F for that pen were adjusted according to the procedure described by Lindemann and Kim (2007). Data were analyzed using SAS 9.4 (SAS Institute Inc., Cary, NC, USA). Pen was the experimental unit for all analyses. Normality of residuals was confirmed and outliers were tested for using the UNIVARIATE procedure of SAS. Outliers were defined as observations with internally studentized residuals less than −3 or greater than 3 and removed from analysis. One outlier observation from each of the following variables (and corresponding dietary treatment) was identified and removed: hot carcass weight (control diet), heart weight (33% hybrid rye replacement diet), ultimate loin

Table 2. Analyzed composition (as-is) of hybrid rye and experimental diets with increasing replacement of corn with hybrid rye

	Phase 1: Grower (days 1 to 35)[1]				Phase 2: Early finisher (days 35 to 70)[1]				Phase 3: Late finisher (days 70 to 97)[1]				
Item	0%	33%	66%	100%	0%	33%	66%	100%	0%	33%	66%	100%	Hybrid rye
Dry matter, %	86.76	87.28	87.75	88.05	86.59	87.21	87.66	87.99	86.88	86.83	87.52	88.04	87.36
Ash, %	4.77	4.52	4.69	4.88	3.50	3.61	3.85	4.00	3.38	3.13	3.51	3.63	1.50
GE[2], kcal/kg	3,979	3,968	3,977	3,969	3,963	3,980	3,972	3,964	3,969	3,963	3,961	3,967	3,819
ME[3], kcal/kg	3,429	3,375	3,320	3,267	3,341	3,379	3,315	3,252	3,454	3,394	3,319	3,257	3,150
Starch, %	40.23	40.75	38.44	37.34	53.36	55.23	46.76	44.26	50.62	48.43	49.33	45.04	55.20
Crude protein, %	17.16	17.81	18.25	19.16	12.86	13.59	14.41	15.05	12.03	12.65	13.36	13.84	8.84
IDF[2], %	11.00	12.30	12.30	13.50	9.80	10.60	11.40	13.30	9.20	10.90	12.90	14.20	14.50
SDF[2], %	ND[2]	0.80	1.60	1.70	ND[2]	0.60	0.40	2.10	0.20	0.10	0.40	1.10	3.70
TDF[2], %	11.00	13.10	13.90	15.20	9.80	11.20	11.90	15.40	9.40	11.00	13.30	15.30	18.20
AEE[2], %	4.73	3.69	4.06	3.68	5.37	5.13	5.09	4.99	6.02	5.25	4.79	4.62	1.63
EE[2], %	3.55	3.07	2.88	2.55	3.77	3.36	3.06	2.61	3.93	3.47	2.52	2.21	0.72
Fatty acids[4], % of EE													
16:0	21.39	20.41	18.21	18.00	14.70	14.92	15.04	14.95	15.27	17.04	15.26	15.18	17.19
16:1	0.14	0.13	0.17	0.15	0.11	0.11	0.12	0.15	0.12	0.13	0.12	0.13	0.24
18:0	5.54	5.13	4.60	4.58	3.49	3.59	3.57	3.73	3.69	4.04	3.65	3.72	0.75
18:1	29.84	28.11	24.43	21.93	25.48	25.03	23.74	21.01	27.58	28.07	23.56	21.46	12.70
18:2	28.94	32.14	39.42	40.71	47.90	47.04	46.94	47.34	44.59	39.94	46.27	47.41	54.73
18:3	1.85	2.44	3.77	4.76	3.54	3.93	4.47	5.58	2.95	2.88	4.41	5.35	6.34
20:1	0.27	0.31	0.33	0.41	0.04	0.04	0.05	0.06	0.05	0.32	0.05	0.06	1.02
Amino acids, %													
Arg	1.01	1.16	1.26	1.24	0.78	0.82	0.85	0.89	0.65	0.73	0.74	0.83	0.52
His	0.42	0.46	0.48	0.47	0.35	0.35	0.35	0.35	0.30	0.32	0.32	0.33	0.22
Ile	0.74	0.81	0.87	0.85	0.57	0.58	0.60	0.62	0.50	0.54	0.54	0.57	0.36
Leu	1.46	1.46	1.49	1.40	1.23	1.16	1.08	0.02	1.10	1.08	0.98	0.95	0.63
Lys	1.00	1.12	1.21	1.17	0.88	0.92	0.93	1.02	0.76	0.79	0.80	0.87	0.40
Met	0.23	0.26	0.29	0.30	0.21	0.22	0.25	0.23	0.18	0.19	0.20	0.22	0.17
Cys	0.26	0.28	0.32	0.32	0.22	0.24	0.26	0.26	0.21	0.23	0.24	0.26	0.23
Phe	0.85	0.92	0.99	0.99	0.68	0.70	0.71	0.73	0.59	0.64	0.65	0.68	0.48
Thr	0.63	0.71	0.75	0.77	0.56	0.63	0.58	0.61	0.49	0.55	0.52	0.58	0.33
Trp	0.21	0.22	0.24	0.24	0.17	0.17	0.18	0.19	0.14	0.14	0.16	0.16	0.12
Val	0.78	0.86	0.93	0.92	0.61	0.63	0.68	0.70	0.56	0.61	0.61	0.65	0.43

[1]The percentages indicate the amount of corn that was replaced by hybrid rye.
[2]GE, gross energy; IDF, insoluble dietary fiber; SDF, soluble dietary fiber; TDF, total dietary fiber; AEE, acid-hydrolyzed ether extract; EE, ether extract; ND, not detected.
[3]ME, metabolizable energy. Calculated concentration of ME based on the value 3,150 kcal/kg ME in hybrid rye (McGhee and Stein, 2020), and values for all other ingredients were obtained from NRC (2012).
[4]Palmitic acid (16:0), palmitoleic acid (16:1), stearic acid (18:0), oleic acid (18:1), linoleic acid (18:2), linolenic acid (18:3), and gondoic acid (20:1).

pH (control diet), loin b* (100% hybrid rye replacement diet), backfat b* (66% hybrid rye replacement diet), and full and empty gastrointestinal weight (control diet). Data were analyzed by the MIXED procedure and the statistical model included the fixed effect of diet and random effect of replicate. Ending live weight was used as a covariate for analyzing all carcass traits. Least square means were calculated for each treatment group using the LSMEANS statement in PROC MIXED. Contrast statements were used to determine linear and quadratic effects of including graded levels of hybrid rye in the diets. Results were considered significant at $P \leq 0.05$ and considered a trend at $0.05 < P \leq 0.10$.

Results

The chemical compositions of diets and the hybrid rye ingredient were within expected ranges (Table 2). The hybrid rye used in the experiment contained 1.69 mg/kg ergot alkaloids. In the grower phase, average pig body weight tended to be reduced (linear, $P < 0.10$) as hybrid rye inclusion in the diet increased, but there were no differences in body weight at any other time point (Table 3). ADG was linearly decreased ($P < 0.05$) as hybrid rye inclusion in the grower diet increased, but ADG was not different among treatments in the early finisher phase. A tendency (quadratic, $P < 0.10$) was observed for ADG to increase and then decrease as hybrid rye inclusion in the late finisher diets was increased. For the early finisher phase, ADG did not differ among treatments. ADFI in the grower phase was linearly reduced ($P < 0.05$) as hybrid rye in the diet increased. Similarly, in the late finisher phase, ADFI tended to be reduced (linear, $P < 0.10$) as hybrid rye was added to the diet, but no differences were observed for ADFI in the early finisher phase or overall. Gain:feed did not differ among treatments in the grower phase or overall, but there was a trend (linear, $P < 0.10$) for G:F to increase with increased hybrid rye in the diet during the early finisher phase. In the late finisher phase, G:F increased and then was reduced (quadratic, $P < 0.05$) as hybrid rye inclusion in the diet increased.

No differences in ending live weight, hot carcass weight, carcass yield, backfat thickness, loin eye area, fat-free lean, drip loss, or loin ultimate pH were observed among treatments (Table 4). Loin visual color score decreased (linear, $P < 0.05$) with dietary inclusion of hybrid rye, but loin visual marbling, subjective firmness, instrumental color, cook loss, and shear force did not differ among treatments. Backfat color was paler (L*; linear, $P < 0.05$) with greater amounts of rye in the diet, but backfat redness (a*) and yellowness (b*) were not different among treatments. Weights of heart, kidney, liver, and empty gastrointestinal tracts increased (linear, $P < 0.05$) with increased hybrid rye in the diet, and there was a tendency (linear, $P < 0.10$) for full gastrointestinal tracts to be heavier with increased hybrid rye in the diet. Trained sensory analysis indicated no difference for loin tenderness or juiciness among treatments, but a linear reduction ($P < 0.05$) was observed for flavor as the inclusion of hybrid rye in the diet increased.

Discussion

Since its introduction to Canada and the United States in 2014 and 2016, respectively, the production of hybrid rye has increased in North America. The yield per hectare of hybrid rye is greater than the yield of open-pollinated rye; hybrid rye also yields more than other small grains when managed correctly (Geiger and Miedaner, 1999, 2009; Jørgensen et al., 2007; Hübner et al., 2013; Schittenhelm et al., 2013; Laidig et al., 2017). Compared with corn and small grains such as wheat and barley, rye is more tolerant of cold temperatures, water and nutrient scarcity, and sandy or acidic soils (Evans and Scoles, 1976; Geiger and Miedaner, 2009; Jürgens et al., 2012), and introducing a new crop to a rotation can help with weed and disease control. New rye hybrids are less susceptible to ergot contamination and have reduced presence of antinutritional factors compared with conventional open-pollinated rye (Schwarz et al., 2015; Miedaner and Geiger, 2015).

Table 3. Growth performance of pigs fed experimental diets in which either 0%, 33%, 66%, or 100% of corn was replaced with hybrid rye[1]

	Corn replacement rate[2]					P-value	
Item	0%	33%	66%	100%	SEM	Linear	Quadratic
Average body weight, kg							
Day 1	23.70	23.66	23.70	23.69	0.730	0.996	0.976
Day 35	55.74	53.78	52.66	52.36	1.443	0.092	0.569
Day 70	92.44	91.78	90.21	89.74	2.161	0.325	0.965
Day 97	120.05	122.14	118.42	116.89	2.632	0.271	0.497
Average daily gain, kg							
Phase 1: Grower, day 1 to 35	0.91	0.86	0.83	0.82	0.024	0.006	0.367
Phase 2: Early finisher, day 35 to 70	1.05	1.09	1.07	1.07	0.031	0.733	0.472
Phase 3: late finisher, day 70 to 97	1.02	1.13	1.05	1.01	0.038	0.454	0.068
Overall: day 1 to 97	0.99	1.02	0.98	0.96	0.022	0.156	0.349
Average daily feed intake, kg							
Phase 1: Grower, day 1 to 35	1.75	1.67	1.57	1.57	0.048	0.005	0.355
Phase 2: Early finisher, day 35 to 70	2.66	2.66	2.62	2.56	0.079	0.356	0.675
Phase 3: Late finisher, day 70 to 97	3.21	3.30	3.03	3.08	0.085	0.079	0.826
Overall: day 1 to 97	2.45	2.48	2.36	2.35	0.064	0.130	0.786
Gain:feed							
Phase 1: Grower, day 1 to 35	0.52	0.52	0.53	0.52	0.008	0.830	0.944
Phase 2: Early finisher, day 35 to 70	0.40	0.41	0.41	0.42	0.009	0.067	0.753
Phase 3: Late finisher, day 70 to 97	0.33	0.34	0.35	0.33	0.007	0.825	0.041
Overall: day 1 to 97	0.41	0.41	0.42	0.41	0.004	0.283	0.177

[1]Least square means for dietary treatments represent eight observations.
[2]The percentages indicate the amount of corn that was replaced by hybrid rye.

Table 4. Carcass characteristics and loin quality of pigs fed experimental diets in which either 0%, 33%, 66%, or 100% of corn was replaced with hybrid rye[1]

	Corn replacement rate[2]					P-value	
Item	0%	33%	66%	100%	SEM	Linear	Quadratic
Ending live weight, kg	117.00	117.71	115.04	114.30	2.981	0.202	0.697
Hot carcass weight[3], kg	88.40	89.25	88.50	88.24	0.467	0.541	0.226
Carcass yield, %	77.07	77.24	76.68	76.51	0.440	0.265	0.696
Fat thickness, cm	1.61	1.77	1.62	1.66	0.315	0.993	0.680
Loin eye area, cm^2	55.51	55.81	54.26	54.24	5.25	0.448	0.918
Fat-free lean[4], %	57.09	56.34	56.55	56.59	2.173	0.742	0.649
Drip loss, %	4.36	4.02	4.28	4.16	0.724	0.906	0.859
Organ weight, kg							
Heart	0.35	0.36	0.40	0.38	0.014	0.024	0.341
Kidney	0.37	0.38	0.42	0.43	0.021	0.003	0.974
Liver	1.71	1.86	1.98	2.09	0.089	<0.001	0.773
Full gastrointestinal tract	6.11	6.01	6.56	6.62	0.272	0.090	0.756
Empty gastrointestinal tract	4.15	4.16	4.50	4.52	0.126	0.016	0.980
Loin quality traits							
Ultimate pH	5.45	5.46	5.43	5.47	0.026	0.737	0.417
Visual color[5]	3.19	2.94	2.94	2.75	0.106	0.011	0.765
Visual marbling[6]	1.61	1.60	1.39	1.90	0.242	0.386	0.126
Subjective firmness[7]	3.11	2.97	3.02	2.91	0.120	0.315	0.913
Lightness, L*[8]	46.33	47.22	46.75	48.19	0.933	0.232	0.772
Redness, a*[8]	8.04	8.35	8.04	7.88	0.504	0.705	0.599
Yellowness, b*[8]	4.54	5.00	4.72	4.39	0.391	0.667	0.295
Backfat color							
Lightness, L*[8]	72.42	72.72	73.17	73.34	0.483	0.036	0.839
Redness, a*[8]	3.76	4.00	3.83	3.90	0.412	0.866	0.785
Yellowness, b*[8]	5.30	5.67	6.01	5.84	0.305	0.125	0.326
Cook loss, %							
Internal temperature 63 °C	18.45	19.28	16.08	18.52	0.964	0.497	0.409
Internal temperature 71 °C	18.46	17.79	16.95	19.17	1.052	0.786	0.180
Warner–Bratzler shear force, kg							
Internal temperature 63 °C	3.36	3.29	3.13	3.41	0.205	0.993	0.397
Internal temperature 71 °C	3.49	3.26	3.64	3.66	0.223	0.361	0.539
Sensory characteristics[9]							
Tenderness	8.93	9.30	8.83	8.94	0.225	0.666	0.563
Juiciness	8.83	8.80	8.78	8.63	0.156	0.379	0.692
Flavor	1.73	1.69	1.69	1.53	0.052	0.016	0.240

[1]Least square means for dietary treatments represent seven to eight observations.
[2]The percentages indicate the amount of corn that was replaced by hybrid rye.
[3]Hot carcass weight included leaf weight.
[4]Fat-free lean = (8.588 + (0.465 × hot carcass weight, lbs) – (21.896 × backfat thickness, in) + (3.005 × loin eye area, in^2))/hot carcass weight, lbs) × 100.
[5]National Pork Producers Council color based on the 1999 standards measured in half-point increments where 1 = palest and 6 = darkest.
[6]National Pork Producers Council marbling based on the 1999 standards measured in half-point increments where 1 = least amount of marbling and 6 = greatest amount of marbling.
[7]National Pork Producers Council firmness based on the 1991 scale measured in half-point increments where 1 = softest and 5 = firmest.
[8]L*, a*, and b* measure darkness, redness, and yellowness, respectively, where greater values indicate a lighter color, a redder color, or a more yellow color, respectively.
[9]Sensory characteristics were scored in loin chops cooked to an internal temperature of 63 °C by trained panelists using the Sensory Guidelines from the American Meat Science Association (AMSA, 2015) on a scale from 0 to 15, where 0 = extremely tough, dry, or not flavorful and 15 = extremely tender, juicy, or flavorful.

Hybrid rye contains a similar quantity of standardized ileal digestible amino acids and a greater quantity of standardized total tract digestible P compared with corn (McGhee and Stein, 2018, 2019). The fiber composition in hybrid rye primarily consists of arabinoxylan, fructooligosaccharides, cellulose, and mixed-linked ß-glucans, and compared with corn, wheat, barley, and sorghum, the fiber from hybrid rye is more fermentable by growing pigs (McGhee and Stein, 2020). The metabolizable energy in hybrid rye fed to growing pigs is approximately 3,500 kcal/kg (dry matter basis), which is less than in corn and wheat, but not different from barley or sorghum (McGhee and Stein, 2020).

Finishing pigs fed hybrid rye instead of barley had greater ADG and ADFI (Schwarz et al., 2015, 2016), and overall ADG, ADFI, and G:F were not different when wheat and barley in diets for growing and finishing pigs were substituted with 50% hybrid rye (Bussières, 2018). However, ADFI was reduced when pigs were fed diets in which hybrid rye replaced wheat and this reduction was most pronounced in the finishing phases of growth (Smit et al., 2019). As a result, ADG also decreased as the inclusion of hybrid rye in the diet increased. However, results of research in which hybrid rye replaces corn in diets for growing-finishing pigs have not been reported, but if given a choice, growing pigs prefer diets containing corn to diets containing hybrid rye (McGhee and Stein, 2021). Rye contains more volatile compounds associated with bitter flavors (Grosch and Schieberle, 1997; Heiniö et al., 2003; Poutanen et al., 2014). It is, therefore, possible that ADFI decreased in the first phase of the present experiment as hybrid rye inclusion in the diet increased because of the inexperience of pigs with the flavor of hybrid rye. It is likely that if pigs are adapted to consuming hybrid rye from weaning, ADFI will not be reduced when hybrid rye is included in grower diets, but this hypothesis has not been experimentally verified. As a consequence, one of the possible reasons why ADFI of pigs was not influenced by inclusion of hybrid rye during the early finisher phase is that at that time, pigs were already adapted to consuming hybrid rye and they had, therefore, no aversion to the rye diets. Although flowability of diets was not measured, feed flowed freely in the feeders and it is unlikely that the differences in ADFI observed during the grower period were caused by poor flowability of diets containing hybrid rye.

Hybrid rye contains more insoluble and soluble dietary fiber than corn (McGhee and Stein, 2018, 2020). Soluble fiber in rye increases the viscosity of the liquid phase of digesta in pigs (Thacker et al., 1999; Bach Knudsen et al., 2005; Le Gall et al., 2009, 2010), and this effect may trigger feelings of satiety in monogastric animals (Kristensen and Jensen, 2011). Insoluble fiber contributes to swelling of the solid phase of digesta, which may increase gut fill of pigs (Avelar et al., 2010; Ndou et al., 2013; De Jong et al., 2014). As a consequence, physical gut fill and satiation may have been the primary reason for the tendency for reduced ADFI that was observed in late finishing pigs as hybrid rye inclusion increased in the diet, as has also been observed when hybrid rye replaced wheat (Smit et al., 2019).

Hybrid rye contains less metabolizable energy than corn when fed to 28 kg pigs (McGhee and Stein, 2020), but the observation that G:F was not reduced in pigs fed diets containing hybrid rye indicates that hybrid rye is well utilized by finishing pigs. The observation that weights of gastrointestinal tracts were greater from pigs fed hybrid rye indicates that more fermentation of fiber occurred in pigs fed hybrid rye (Jørgensen et al., 1996). Therefore, the difference in metabolizable energy between hybrid rye and corn may be less pronounced in finishing pigs than in growing pigs because fermentative capacity increases with age (Le Goff et al., 2002). It is also possible that the dietary fiber in hybrid rye increased satiation and reduced physical activity of pigs and, therefore, decreased the maintenance energy.

When hybrid rye substituted barley in diets for growing-finishing pigs, carcass weight and slaughter value were greater for pigs fed hybrid rye (Schwarz et al., 2015). However, with the exception of backfat thickness, which was reduced, no effects of replacing barley by rye were observed (Bussières, 2018). The fact that carcass traits were not affected by dietary treatments in the present experiment is, therefore, in agreement with previous data indicating that inclusion of hybrid rye in diets generally does not change carcass composition. Although organ weights were greater as the inclusion of hybrid rye in the diet increased, carcass yield was not affected. The reason for the increased kidney and liver weights may be the greater quantities of N in diets containing hybrid rye compared with the control diet (Ruusunen et al., 2007). The paler color of loins (visual color score) and backfat (instrumental L*) that were observed for pigs fed greater amounts of hybrid rye are in agreement with effects of including barley instead of corn in diets for finishing pigs (Kim et al., 2014). Corn contains more carotenoids than other cereal grains, but reducing the concentration of corn in diets does not always result in less yellow-colored loins or backfat (Carr et al., 2005; Kim et al., 2014). The reduction in loin flavor scores by trained sensory panelists can likely be explained by the presence of bitter-tasting phenolic compounds in hybrid rye grain (Grosch and Schieberle, 1997; Heiniö et al., 2003; Poutanen et al., 2014). However, although statistically significant differences were observed, flavor scores for loins were numerically low for all samples, and the difference between the average scores for pigs fed diets containing only corn and no rye and pigs fed diets with only rye and no corn was only 0.20 units on a scale from 0 to 15.

Conclusion

Feed intake tended to be reduced with greater inclusions of hybrid rye in the grower and late finisher pig diets, but it is possible that this reduction may be ameliorated if pigs are introduced to hybrid rye earlier in life. Feed efficiency was not affected by inclusion of hybrid rye in diets, indicating that hybrid rye was well utilized by growing-finishing pigs. Most carcass traits did not differ among treatments, although organ weights were heavier as dietary inclusion of hybrid rye increased. Results of the experiment support the hypothesis that hybrid rye may be included in diets for growing-finishing pigs at the expense of corn without compromising the overall growth performance.

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Conflict of interest statement

The authors have no conflicts of interest.

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