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# Inclusion of hybrid rye in diets for weanling pigs does not compromise daily gain, but may reduce diarrhea incidence despite pigs having preference for consuming corn over hybrid rye

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ABSTRACT

Two experiments were conducted to test the hypotheses that feed preference and growth performance will not differ if hybrid rye replaces some of the corn in diets for nursery pigs. In experiment 1, 40 barrows (9.2 ± 1.0 kg) were housed in 20 pens for eight days. Each pen had two identical feeders containing a corn-based diet or a diet in which 500 g/kg of the corn was substituted with hybrid rye, and feeder positions were switched daily. In experiment 2, 160 pigs (6.0 ± 0.7 kg) were randomly allotted to 40 pens and five treatments. Phase 1 diets were fed from day 1–7 (0, 30, 60, 90, or 120 g/kg rye), whereas phase 2 (0, 50, 110, 160, or 210 g/kg rye) and phase 3 (0, 150, 300, 450, or 600 g/kg rye) diets were fed from day 7–21 and day 21–34, respectively. Body weights were recorded at the start and end of each phase, fecal scores were recorded every other day, and blood samples were obtained from one pig per pen on day 21 and 34. Results of experiment 1 indicated that preference was greater ($P < 0.05$) for the corn-based diet than for the corn-hybrid rye mixed diet on days 2, 3, 6, and 8, and for the overall period. Overall, pigs preferred the corn-based diet over the rye-based diet by a ratio of 5.7–4.3. In experiment 2, there were no differences among treatments for final body weight or average daily gain. During phase 3 and overall experiment, pigs fed diets with 600 g/kg hybrid rye and no corn consumed the most feed (quadratic, $P < 0.05$). Consequently, gain:feed in phase 3 and overall was reduced (quadratic, $P < 0.05$) as hybrid rye replaced corn in the diet. Diarrhea incidence decreased (quadratic, $P < 0.05$) with 60 or 90 g/kg hybrid rye in the phase 1 diet. Blood urea N was elevated (day 21, quadratic, $P < 0.05$; day 34, linear, $P < 0.05$) as dietary hybrid rye inclusion increased. In conclusion, castrated male weaned pigs had a preference for corn-based diets over diets containing a mix of corn and hybrid rye, but replacing up to 300, 400, or 1000 g per kg of corn in phase 1, 2, and 3 diets for weanling pigs did not result in differences in average daily gain or final body weight of pigs, but gain to feed ratio was reduced for pigs fed the diets with the greatest inclusion of hybrid rye because feed intake was increased. Hybrid rye may also modulate the immune response by influencing blood cell concentrations and reducing diarrhea incidence in pigs.

*Abbreviations:* ADG, average daily gain; ADFI, average daily feed intake; G:F, gain:feed.

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## 1. Introduction

Compared with corn, hybrid rye contains similar amounts of standardized ileal digestible amino acids, a greater concentration of standardized total tract digestible P, and approximately 94% of the metabolizable energy (McGhee and Stein, 2018, 2019, 2020). Hybrid rye contains more fermentable dietary fiber than corn and substantially more fructooligosaccharides compared with other cereal grains (Hansen et al., 2003; Karppinen et al., 2003; McGhee and Stein, 2020). Fermentation of rye fiber has the potential to improve gut health of pigs by increasing synthesis of butyrate, thereby reducing pH in the large intestine, and supporting the proliferation of beneficial bacteria in the gut (Bach Knudsen et al., 2016, 2017; Zhao et al., 2013). In contrast, rye is perceived by humans to be more bitter-tasting than other cereal grains (Katina et al., 2014), and preconceptions exist among swine producers that feed intake will be compromised by pigs fed rye due to poor palatability. Few scientific studies have evaluated feed preference of pigs with diets containing rye (Solà-Oriol et al., 2009a, 2009b), and limited published data exist for growth performance of nursery pigs fed diets containing hybrid rye (Chuppava et al., 2020; Wilke et al., 2020; Ellner et al., 2021). To our knowledge, no data have been reported for feed preference of pigs fed a diet based on corn and soybean meal compared with a diet containing hybrid rye, and there are no published data comparing growth performance of weanling pigs fed diets containing corn or hybrid rye. Therefore, two experiments were conducted to test the hypothesis that feed preference and growth performance will not be affected if hybrid rye replaces some of

**Table 1**
Composition of diets in experiment 1 (as-is basis).

| Item | Control | Hybrid rye |
|---|---|---|
| Ingredient, g/kg | | |
| Ground hybrid rye | – | 262.0 |
| Ground corn | 523.7 | 262.0 |
| Soybean meal | 245.0 | 245.0 |
| Whey, dried | 120.0 | 120.0 |
| Fish meal | 60.0 | 60.0 |
| Soybean oil | 30.0 | 30.0 |
| Ground limestone | 8.8 | 9.3 |
| Dicalcium phosphate | 2.5 | 1.5 |
| L-lysine HCl, 78% | 3.5 | 3.4 |
| DL-methionine, 98% | 1.1 | 1.3 |
| L-threonine, 98% | 0.9 | 1.0 |
| Sodium chloride | 3.0 | 3.0 |
| Vitamin-mineral premix[a] | 1.5 | 1.5 |
| Analyzed composition | | |
| Dry matter, g/kg | 883.8 | 887.1 |
| Ash, g/kg | 60.5 | 53.7 |
| Gross energy, MJ/kg | 16.97 | 16.75 |
| Metabolizable energy[b], MJ/kg | 14.47 | 14.22 |
| Starch, g/kg | 341.7 | 281.5 |
| Insoluble dietary fiber, g/kg | 108.0 | 110.0 |
| Soluble dietary fiber, g/kg | 12.0 | 20.0 |
| Total dietary fiber, g/kg | 120.0 | 130.0 |
| Acid-hydrolyzed ether extract, g/kg | 53.8 | 55.4 |
| Crude protein, g/kg | 201.6 | 202.4 |
| Amino acids, g/kg | | |
| Arg | 13.3 | 12.0 |
| His | 5.3 | 4.9 |
| Ile | 9.8 | 9.1 |
| Leu | 17.5 | 15.6 |
| Lys | 14.8 | 15.1 |
| Met | 4.5 | 4.5 |
| Cys | 3.1 | 3.1 |
| Phe | 10.3 | 9.5 |
| Thr | 8.7 | 8.8 |
| Trp | 2.6 | 2.7 |
| Val | 10.5 | 10.0 |

[a] The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 11,150 IU; vitamin $D_3$ as cholecalciferol, 2210 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.

[b] Metabolizable energy was calculated rather than analyzed and based on the value 3150 kcal/kg metabolizable energy in hybrid rye (McGhee and Stein, 2020a), and values for all other ingredients according to NRC (2012).

**Table 2**
Ingredient composition of diets with increasing rate of hybrid rye replacement for corn, experiment 2 (as-is basis).

| Item | Phase 1 (day 1 – 7)[a] | | | | | Phase 2 (day 7 – 21)[a] | | | | | Phase 3 (day 21 – 34)[a] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| g/kg corn replacement: | 0 | 75 | 150 | 225 | 300 | 0 | 100 | 200 | 300 | 400 | 0 | 250 | 500 | 750 | 1000 |
| Ground hybrid rye | – | 30.0 | 60.0 | 90.0 | 120.0 | – | 53.4 | 106.8 | 160.3 | 213.6 | – | 150.7 | 301.6 | 452.5 | 603.4 |
| Ground corn | 399.6 | 369.9 | 339.8 | 309.8 | 279.8 | 534.0 | 480.7 | 427.4 | 373.9 | 320.7 | 602.8 | 452.4 | 301.6 | 150.9 | – |
| Whey, dried | 250.0 | 250.0 | 250.0 | 250.0 | 250.0 | 120.0 | 120.0 | 120.0 | 120.0 | 120.0 | – | – | – | – | – |
| Soybean meal | 200.0 | 200.0 | 200.0 | 200.0 | 200.0 | 245.0 | 245.0 | 245.0 | 245.0 | 245.0 | 350.0 | 350.0 | 350.0 | 350.0 | 350.0 |
| Fish meal | 80.0 | 80.0 | 80.0 | 80.0 | 80.0 | 60.0 | 60.0 | 60.0 | 60.0 | 60.0 | – | – | – | – | – |
| Blood plasma | 35.0 | 35.0 | 35.0 | 35.0 | 35.0 | – | – | – | – | – | – | – | – | – | – |
| Soybean oil | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 | 20.0 |
| Limestone | 7.6 | 7.4 | 7.4 | 7.4 | 7.4 | 8.7 | 8.7 | 8.8 | 8.9 | 9.1 | 8.6 | 9.1 | 9.5 | 9.8 | 10.3 |
| Dicalcium phosphate | – | – | – | – | – | 2.5 | 2.3 | 2.1 | 1.9 | 1.7 | 10.5 | 9.7 | 9.0 | 8.5 | 7.8 |
| L-lysine HCl, 780 g/kg | 2.1 | 2.0 | 2.0 | 2.0 | 2.0 | 3.4 | 3.4 | 3.4 | 3.4 | 3.3 | 2.5 | 2.4 | 2.4 | 2.3 | 2.2 |
| DL-methionine, 980 g/kg | 0.9 | 0.9 | 1.0 | 1.0 | 1.0 | 1.0 | 1.1 | 1.1 | 1.2 | 1.2 | 0.6 | 0.7 | 0.8 | 0.9 | 1.1 |
| L-threonine, 980 g/kg | 0.3 | 0.3 | 0.3 | 0.3 | 0.3 | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 | 0.5 | 0.5 | 0.6 | 0.6 | 0.7 |
| Salt | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 |
| Vitamin-mineral premix[b] | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 |

[a] The proportions (g/kg) indicate the amount of corn that was replaced with hybrid rye in the diets.

[b] The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 11,150 IU; vitamin $D_3$ as cholecalciferol, 2210 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.

the corn in diets fed to weanling pigs.

## 2. Materials and methods

Two experiments were conducted following protocols that were approved by the Institutional Animal Care and Use Committee at the University of Illinois. Pigs were the offspring of Line 359 boars and Camborough sows (Pig Improvement Company, Henderson, TN, USA).

### *2.1. Animals, housing, and experimental design*

#### *2.1.1. Experiment 1*

Forty barrows with an initial body weight of 9.2 ± 1.0 kg at approximately two weeks post-weaning were housed for eight days in pens with slatted floors, a nipple waterer, and two identical plastic feeders attached to the front gate of each pen. There were two pigs per pen, for a total of 20 pens. Two experimental diets were formulated (Table 1). One diet that contained corn as the only cereal grain was formulated to meet or exceed the estimated requirements for standardized ileal digestible amino acids, vitamins, and minerals for 7–11 kg pigs (NRC, 2012). An additional diet in which approximately 50% of the corn in the initial diet was replaced with hybrid rye (KWS Lochow GmbH, Bergen, Germany) was also formulated. All pigs had *ad libitum* access to the corn diet in one feeder and to the corn-hybrid rye diet in the other feeder. Positions of the two feeders were switched daily at 0800 h to minimize the effect of feeder location preference and at that time, all feeders were weighed to calculate daily feed disappearance. Afterwards, daily feed allowance was also recorded. Because all pens received the same diets, there were 20 replicate pens in the experiment.

#### *2.1.2. Experiment 2*

One hundred and sixty pigs with an initial body weight of 6.0 ± 0.7 kg were weaned at 19–21 days of age and randomly allotted to five dietary treatments in a randomized complete block design with body weight used as the blocking factor. Forty pens were used with four pigs per pen and eight replicate pens per treatment. Sex was balanced within pen and among treatments. Pigs were housed in an environmentally controlled nursery barn with fully slatted floors, a nipple waterer, and a stainless steel feeder. Water and feed were available on an *ad libitum* basis.

Pigs were fed experimental diets for 34 days, and a 3-phase feeding program was used. Phase 1 diets were fed for seven days post-weaning, phase 2 diets were fed from day 7–21, and phase 3 diets were fed from day 21–34. In total, 15 diets were formulated (Table 2), and all diets were fed in mash form. In each phase, a control diet primarily based on corn and soybean meal was formulated. The additional four diets within each phase contained increasing levels of hybrid rye, which was included at the expense of corn. The same source of hybrid rye used in experiment 1 was used in experiment 2. In phase 1, inclusion of hybrid rye was 30, 60, 90, or 120 g/kg, respectively. In phase 2, inclusion of hybrid rye was 53, 107, 160, or 214 g/kg, respectively, and in phase 3, inclusion of hybrid rye in each diet was 150, 302, 453, or 603 g/kg.

All diets were formulated to meet or exceed the estimated requirements for standardized ileal digestible amino acids, vitamins, and minerals for pigs in each of the three phases (NRC, 2012). However, diets were not formulated to be isocaloric or isonitrogenous; therefore, as hybrid rye inclusion in the diet increased, the calculated concentration of total dietary fiber and crude protein increased, whereas the concentration of metabolizable energy decreased.

Individual pig weights were obtained at the beginning of the experiment and at the conclusion of each phase. Feed allowance was recorded daily, and feed left in the feeders at the conclusion of each phase was weighed to calculate feed disappearance. If a pig was removed from a pen during the experiment, individual pig weights and the weight of the feed in the feeder at the time of removal were recorded. Fecal scores were assessed visually for each pen as a whole every other day by two independent observers using a score from 1 to 5 (1 = normal feces; 2 = moist feces; 3 = mild diarrhea; 4 = severe diarrhea; and 5 = watery diarrhea).

Two 3-mL blood samples were collected *via* the jugular vein from one pig per pen on the last day of phase 2 and on the last day of phase 3. An equal number of barrows and gilts were sampled within treatment, and the same pigs were sampled at each time point. Of the two samples of blood obtained per pig, the first was collected in a vacutainer tube containing ethylenediaminetetraacetic acid as an anti-coagulant, immediately placed on ice to prevent blood clotting, and used for complete blood count analysis on a multiparameter automated hematology analyzer (CELL-DYN 3700, Abbott Laboratories, Abbott Park, IL, USA). The second sample of blood was collected in a vacutainer tube containing spray-coated silica as a serum clot activator, allowed to clot, and centrifuged at 4000× *g* for 13 min at room temperature. Serum was removed from centrifuged tubes and stored at −20 °C until analysis for total protein, blood urea N, and albumin. Serum analysis was performed using a Beckman Coulter Clinical Chemistry AU analyzer (Beckman Coulter Inc., Brea, CA, USA).

### *2.2. Chemical analysis*

All diet samples were ground through a 1-mm screen (MM4; Schutte Buffalo, NY, USA) prior to chemical analysis. Diet samples were analyzed for dry matter by oven drying at 135 °C for 2 h (method 930.15; AOAC Int, 2007). Samples were also analyzed for ash (method 942.05; AOAC Int, 2007). The gross energy in diets 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), which yields the enzymatically hydrolyzed starch in the sample. Diets were analyzed for N (method 990.03; AOAC Int, 2007) using a Leco Nitrogen Determinator (model FP628, Leco Corp., St. Joseph, MI, USA), and crude

**Table 3**
Analyzed composition of diets with increasing rate of hybrid rye replacement for corn, experiment 2 (as-is basis).

| Item | Phase 1 (day 1 – 7)[a] | | | | | Phase 2 (day 7 – 21)[a] | | | | | Phase 3 (day 21 – 34)[a] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| g/kg corn replacement: | 0 | 75 | 150 | 225 | 300 | 0 | 100 | 200 | 300 | 400 | 0 | 250 | 500 | 750 | 1000 |
| Dry matter, g/kg | 891.3 | 891.8 | 890.6 | 891.2 | 891.5 | 879.1 | 884.1 | 881.1 | 883.2 | 883.9 | 873.2 | 871.9 | 873.4 | 874.7 | 872.0 |
| Ash, g/kg | 60.9 | 63.3 | 58.9 | 63.4 | 62.1 | 50.6 | 56.0 | 54.8 | 55.8 | 59.1 | 48.5 | 46.8 | 44.0 | 47.6 | 46.3 |
| Gross energy, MJ/kg | 16.87 | 16.81 | 16.86 | 16.85 | 16.79 | 16.79 | 16.74 | 16.71 | 16.80 | 16.68 | 165.9 | 16.59 | 16.52 | 16.55 | 16.47 |
| ME[b], MJ/kg | 14.49 | 14.46 | 14.43 | 14.40 | 14.37 | 14.27 | 14.22 | 14.17 | 14.11 | 14.06 | 14.10 | 13.95 | 13.80 | 13.65 | 13.49 |
| Starch, g/kg | 198.7 | 201.9 | 218.3 | 239.6 | 197.5 | 330.2 | 301.1 | 287.8 | 287.0 | 247.1 | 323.3 | 267.0 | 288.5 | 325.7 | 272.0 |
| Crude protein, g/kg | 233.7 | 235.7 | 229.4 | 228.8 | 225.8 | 202.5 | 208.6 | 210.9 | 212.3 | 219.5 | 201.8 | 213.4 | 215.3 | 224.1 | 224.3 |
| Insoluble dietary fiber, g/kg | 85.0 | 84.0 | 81.0 | 86.0 | 86.0 | 92.0 | 90.0 | 97.0 | 99.0 | 103.0 | 113.0 | 123.0 | 124.0 | 133.0 | 147.0 |
| Soluble dietary fiber, g/kg | 6.0 | 8.0 | 15.0 | 10.0 | 10.0 | 8.0 | 21.0 | 15.0 | 17.0 | 15.0 | 17.0 | 15.0 | 18.0 | 28.0 | 28.0 |
| Total dietary fiber, g/kg | 91.0 | 92.0 | 96.0 | 96.0 | 96.0 | 100.0 | 111.0 | 112.0 | 116.0 | 118.0 | 130.0 | 139.0 | 142.0 | 160.0 | 176.0 |
| AEE[c], g/kg | 44.5 | 44.6 | 48.5 | 42.6 | 40.5 | 51.2 | 49.4 | 49.0 | 49.8 | 49.0 | 50.9 | 47.9 | 32.6 | 31.4 | 25.0 |
| Amino acids, g/kg | | | | | | | | | | | | | | | |
| Arg | 12.5 | 12.9 | 12.9 | 12.6 | 13.8 | 11.8 | 12.4 | 12.0 | 14.0 | 13.0 | 12.5 | 14.5 | 15.1 | 14.0 | 14.4 |
| His | 5.3 | 5.5 | 5.4 | 5.4 | 5.8 | 4.8 | 5.0 | 4.8 | 5.5 | 5.2 | 5.0 | 5.7 | 5.8 | 5.5 | 5.5 |
| Ile | 9.9 | 10.0 | 10.0 | 10.0 | 10.5 | 8.8 | 9.4 | 8.5 | 10.2 | 9.9 | 8.7 | 10.3 | 10.5 | 9.8 | 10.0 |
| Leu | 18.5 | 18.9 | 18.6 | 18.4 | 19.4 | 15.9 | 16.7 | 15.2 | 17.6 | 16.9 | 16.2 | 18.1 | 17.9 | 16.7 | 16.5 |
| Lys | 15.6 | 16.7 | 16.2 | 17.2 | 16.5 | 13.0 | 14.0 | 13.4 | 15.4 | 15.1 | 12.3 | 14.2 | 15.1 | 13.9 | 14.6 |
| Met | 4.5 | 4.2 | 4.5 | 4.5 | 4.7 | 4.3 | 4.1 | 3.8 | 5.7 | 4.5 | 3.3 | 4.0 | 4.0 | 4.0 | 4.1 |
| Cys | 3.7 | 4.2 | 3.9 | 3.7 | 4.0 | 2.9 | 2.9 | 2.5 | 3.3 | 3.1 | 2.8 | 3.4 | 3.6 | 3.5 | 3.5 |
| Phe | 10.1 | 10.5 | 10.5 | 10.4 | 11.2 | 9.2 | 9.8 | 9.0 | 10.7 | 10.3 | 9.7 | 11.4 | 11.7 | 10.8 | 11.3 |
| Thr | 9.7 | 10.1 | 10.0 | 9.9 | 10.4 | 7.7 | 8.2 | 7.7 | 9.0 | 8.8 | 7.5 | 8.5 | 9.3 | 8.5 | 8.8 |
| Trp | 2.9 | 2.8 | 3.0 | 2.9 | 3.0 | 2.4 | 2.4 | 2.3 | 2.4 | 2.4 | 2.3 | 2.5 | 2.5 | 2.6 | 2.7 |
| Val | 11.5 | 11.8 | 11.7 | 11.6 | 12.2 | 9.5 | 10.1 | 9.5 | 11.1 | 10.7 | 9.4 | 10.9 | 11.2 | 10.6 | 10.8 |

[a] The proportions (g/kg) indicate the amount of corn that was replaced with hybrid rye in the diets.
[b] ME = metabolizable energy. Calculated concentration of ME was based on the value 3150 kcal/kg ME in hybrid rye (McGhee and Stein, 2020), and values for all other ingredients were obtained from NRC (2012).
[c] AEE = acid-hydrolyzed ether extract.

protein was calculated as 6.25× N. Diets 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). Total dietary fiber was calculated as the sum of insoluble and soluble dietary fiber. Acid-hydrolyzed ether extract in diets was measured by crude fat extraction using petroleum ether (Ankom$^{XT15}$, Ankom Technology, Macedon, NY, USA) following hydrolysis using 3*N* HCl (Ankom$^{HCl}$, Ankom Technology, Macedon, NY, USA). Diets were analyzed for amino acids according to method 982.30 E(a, *b*, c) (AOAC Int, 2007) 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.

### 2.3. Calculations and statistical analysis

#### 2.3.1. Experiment 1

At the conclusion of the experiment, feed preference was calculated using the following equation for each day of the experiment as well as the overall 8-day period (Solà-Oriol et al., 2009a):

$$\text{Preference (\%)} = \left[\frac{\text{intake of individual diet (kg)}}{\text{intake of both diets (kg)}}\right] \times 100$$

Feed intake of individual diets was equated to feed disappearance from feeders, which was measured and recorded daily. Data for feed disappearance and feed preference were analyzed using SAS 9.4 (SAS Institute Inc., 2016). Replications, and therefore, number of pigs used in both experiments, were based on means and SD of parameters obtained in previous experiments with similar designs (Kim et al., 2012). Pen was the experimental unit. Normality of data was confirmed using the UNIVARIATE procedure. Data were analyzed by the paired *t*-test in SAS. Results were considered significant at $P \leq 0.05$.

#### 2.3.2. Experiment 2

Average daily gain (ADG), average daily feed intake (ADFI), gain:feed (G:F), average fecal scores, and diarrhea frequency were calculated for each of the phases as well as over the entire experiment. If a pig was removed from a pen during the experiment, ADFI and G:F were adjusted according to the procedure described by Lindemann and Kim (2007). Pen was considered the experimental unit, and data were summarized for each treatment group. Normality of the residuals was confirmed and outliers were tested using the UNIVARIATE procedure of SAS. Outliers were defined as observations with internally studentized residuals less than −3 or greater than 3, but none were observed. With the exception of diarrhea frequency, data were analyzed by the MIXED procedure, and the statistical model included the fixed effect of diet and the random effect of block. Least square means were estimated for each treatment group using the LSMEANS statement in PROC MIXED. Contrast statements were used to test linear and quadratic effects of including graded levels of hybrid rye in the diets. Diarrhea frequency was analyzed by the GLIMMIX procedure with binomial distribution, and it was expressed as the proportion of the number of observations of fecal scores ≥ 3 divided by the total number of observations. Results were considered significant at $P \leq 0.05$.

## 3. Results

The chemical composition of diets in both experiments were within expected ranges (Tables 1 and 3). In experiment 1, feed

**Table 4**
Daily and overall feed disappearance and feed preference in experiment 1[a].

| Item | Control | Hybrid rye | SD | *P*-value |
|---|---|---|---|---|
| Feed disappearance, kg | | | | |
| Day 1 | 0.83 | 0.77 | 0.12 | 0.282 |
| Day 2 | 1.04 | 0.65 | 0.10 | < 0.001 |
| Day 3 | 0.97 | 0.66 | 0.06 | < 0.001 |
| Day 4 | 0.89 | 0.80 | 0.04 | 0.083 |
| Day 5 | 1.19 | 1.09 | 0.23 | 0.216 |
| Day 6 | 1.46 | 1.10 | 0.22 | 0.014 |
| Day 7 | 1.19 | 0.99 | 0.22 | 0.141 |
| Day 8 | 1.38 | 0.99 | 0.21 | 0.016 |
| Overall | 8.95 | 7.06 | 4.48 | 0.005 |
| Feed preference, % | | | | |
| Day 1 | 52.4 | 47.6 | 16.57 | 0.259 |
| Day 2 | 62.4 | 37.6 | 15.35 | < 0.001 |
| Day 3 | 60.6 | 39.4 | 13.23 | < 0.001 |
| Day 4 | 53.2 | 46.8 | 10.85 | 0.099 |
| Day 5 | 52.7 | 47.3 | 15.64 | 0.227 |
| Day 6 | 57.2 | 42.8 | 15.42 | 0.025 |
| Day 7 | 55.1 | 44.9 | 19.82 | 0.134 |
| Day 8 | 59.3 | 40.7 | 17.87 | 0.016 |
| Overall | 56.6 | 43.4 | 15.87 | 0.005 |

[a] Means represent 20 observations.

disappearance (kg) and feed preference (%) were greater ($P < 0.05$) for the corn-based diet than for the corn-hybrid rye diet on day 2, 3, 6, and 8 and for the overall period (Table 4). No differences in feed disappearance were observed on day 1, 5, and 7. Overall, pigs preferred ($P = 0.005$) the corn-based diet 56.6% of the time and the corn-hybrid rye diet 43.4% of the time.

In experiment 2, there were no differences in average body weight or ADG among treatments (Table 5). During phase 3 and overall, ADFI increased (quadratic, $P < 0.05$) as hybrid rye inclusion in the diet increased because pigs fed the diet in which all the corn was replaced by hybrid rye consumed the most feed. Consequently, G:F in phase 3 and overall decreased with greater inclusion of hybrid rye in the diet (quadratic, $P < 0.05$). No differences were observed for average fecal scores during the experiment (Table 6). However, diarrhea incidence decreased with 60 or 90 g/kg hybrid rye inclusion in phase 1, but not with 120 g/kg hybrid rye inclusion (quadratic, $P = 0.024$) .

On day 21, hybrid rye inclusion in diets did not influence most blood characteristics, including white blood cells (Table 7). However, blood urea N increased (quadratic, $P = 0.04$) as hybrid rye inclusion increased, but no differences were observed for serum albumin or total protein. On day 34, red blood cell concentrations increased with increasing dietary rye (linear, $P = 0.026$) and mean corpuscular volume and mean corpuscular hemoglobin were reduced (linear, $P = 0.014$ and $P = 0.009$, respectively) as hybrid rye inclusion in diets increased (Table 8). The concentration of neutrophils was also reduced at intermediate rye levels, but then increased, as hybrid rye inclusion increased (quadratic, $P = 0.042$). Blood urea N increased (quadratic, $P = 0.007$) as hybrid rye in the diet increased, but serum albumin and total protein were not influenced by hybrid rye.

## 4. Discussion

A 3-phase feeding program was used to match dietary nutrient concentrations to requirements of the pigs (NRC, 2012). By increasing concentrations of rye in diets used in the three phases, a gradual adaptation to rye was attempted. Historically, rye has not been included in swine diets in large quantities due to concerns about ergot contamination and anti-nutritional factors (Friend and MacIntyre, 1969; Antoniou et al., 1981; Bederska-Łojewska et al., 2017). However, in newer varieties of hybrid rye, the risk of ergot contamination is partially mitigated (Hackauf et al., 2012; Miedaner and Geiger, 2015), and hybrid rye contains fewer anti-nutritional factors, including alkylresorcinols and trypsin inhibitors, than older cultivars of rye (Schwarz et al., 2015, 2016). Preconceptions sometimes exist among livestock producers that rye grain has poor palatability (Brooks, 1911; Halpin et al., 1936; Sharma et al., 1981), but there is limited scientific evidence to support claims that feed preference for rye is inherently low in pigs. In contrast, it was concluded that preference for rye by 17-kg pigs is not different from that of corn (Solà-Oriol et al., 2009a) or from that of white rice (Solà-Oriol et al., 2009b). Results of the present experiment indicating that pigs prefer a diet containing corn over a diet containing rye are, therefore, in contrast with the previous data. It is possible that one reason for this difference is that in the present experiment, pigs were fed diets based on corn before they were allotted to dietary treatments, and they may, therefore, have had a preference for the corn diet because that was what they were used to. It is also possible that the increased fiber in rye may have reduced pig preference for the diet containing hybrid rye compared with corn.

Limited data have been reported from experiments in which hybrid rye replaces corn in diets for weanling pigs, but replacing wheat with hybrid rye does not influence growth performance (Chuppava et al., 2020; Wilke et al., 2020; Ellner et al., 2021). In earlier experiments with non-hybrid rye, feed intake and growth appeared to be compromised when rye replaced barley in diets for weanling

**Table 5**
Growth performance of pigs fed diets with increasing rate of hybrid rye replacement for corn, experiment 2[a].

| Item | Phase 1/2/3 corn replacement rate[b] | | | | | | *P* – values | |
|---|---|---|---|---|---|---|---|---|
| g/kg corn replacement: | 0/0/0 | 75/100/250 | 150/200/500 | 225/300/750 | 300/400/1000 | SE | Linear | Quadratic |
| Body weight, kg | | | | | | | | |
| Day 1 | 6.05 | 6.05 | 6.05 | 6.05 | 6.04 | 0.206 | 0.976 | 0.987 |
| Day 7 | 6.60 | 6.64 | 6.56 | 6.61 | 6.70 | 0.216 | 0.791 | 0.761 |
| Day 21 | 9.76 | 9.92 | 9.81 | 9.76 | 10.28 | 0.355 | 0.438 | 0.563 |
| Day 34 | 16.55 | 16.87 | 16.66 | 16.37 | 16.72 | 0.550 | 0.933 | 0.989 |
| Average daily gain, g | | | | | | | | |
| Phase 1, day 1–7 | 78 | 84 | 73 | 80 | 95 | 15 | 0.553 | 0.531 |
| Phase 2, day 7–21 | 226 | 236 | 232 | 225 | 256 | 16 | 0.342 | 0.549 |
| Phase 3, day 21–34 | 522 | 535 | 527 | 509 | 495 | 20 | 0.214 | 0.405 |
| Overall, day 1–34 | 309 | 319 | 312 | 304 | 314 | 13 | 0.938 | 0.984 |
| Average daily feed intake, g | | | | | | | | |
| Phase 1, day 1–7 | 130 | 138 | 121 | 118 | 141 | 12 | 0.936 | 0.360 |
| Phase 2, day 7–21 | 343 | 333 | 334 | 330 | 351 | 20 | 0.842 | 0.449 |
| Phase 3, day 21–34 | 802 | 761 | 770 | 766 | 871 | 30 | 0.134 | 0.016 |
| Overall, day 1–34 | 475 | 458 | 457 | 454 | 507 | 18 | 0.291 | 0.042 |
| Gain:feed | | | | | | | | |
| Phase 1, day 1–7 | 0.556 | 0.599 | 0.571 | 0.669 | 0.626 | 0.086 | 0.446 | 0.885 |
| Phase 2, day 7–21 | 0.658 | 0.714 | 0.693 | 0.680 | 0.727 | 0.021 | 0.129 | 0.905 |
| Phase 3, day 21–34 | 0.654 | 0.700 | 0.687 | 0.664 | 0.580 | 0.023 | 0.018 | 0.004 |
| Overall, day 1–34 | 0.652 | 0.695 | 0.685 | 0.670 | 0.624 | 0.020 | 0.204 | 0.019 |

[a] Least square means represent 8 observations.
[b] The proportions (g/kg) indicate the amount of corn that was replaced with hybrid rye in the diets.

**Table 6**
Average fecal scores and incidence of diarrhea in pigs fed diets with increasing rate of hybrid rye replacement for corn, experiment 2[a].

| Item | Phase 1/2/3 corn replacement rate[b] | | | | | | *P* – values | |
|---|---|---|---|---|---|---|---|---|
| g/kg corn replacement: | 0/0/0 | 75/100/250 | 150/200/500 | 225/300/750 | 300/400/1000 | SE | Linear | Quadratic |
| Average fecal score[c] | | | | | | | | |
| Phase 1, day 1–7 | 2.37 | 2.62 | 2.06 | 1.94 | 2.38 | 0.174 | 0.225 | 0.221 |
| Phase 2, day 7–21 | 2.59 | 2.85 | 2.68 | 2.40 | 2.76 | 0.141 | 0.861 | 0.816 |
| Phase 3, day 21–34 | 1.93 | 2.00 | 1.84 | 1.96 | 1.94 | 0.101 | 0.944 | 0.798 |
| Overall, day 1–34 | 2.28 | 2.46 | 2.22 | 2.13 | 2.36 | 0.091 | 0.571 | 0.487 |
| Diarrhea incidence[d], % | | | | | | | | |
| Phase 1, day 1–7 | 45.83 | 58.33 | 16.67 | 12.50 | 45.83 | 10.170 | 0.106 | 0.024 |
| Phase 2, day 7–21 | 42.86 | 58.93 | 44.64 | 26.79 | 51.79 | 6.677 | 0.457 | 0.531 |
| Phase 3, day 21–34 | 7.14 | 12.50 | 7.14 | 3.57 | 5.36 | 4.419 | 0.278 | 0.809 |
| Overall, day 1–34 | 28.68 | 39.71 | 24.26 | 14.71 | 31.62 | 4.196 | 0.090 | 0.144 |

[a] Least square means for dietary treatments represent 8 observations.
[b] The proportions (g/kg) indicate the amount of corn that was replaced with hybrid rye in the diets.
[c] Fecal scores: 1 = normal feces; 2 = moist feces; 3 = mild diarrhea; 4 = severe diarrhea; and 5 = watery diarrhea.
[d] Incidence of diarrhea calculated as number of days with fecal score ≥ 3 divided by total number of observations.

**Table 7**
Blood analyses from pigs fed diets with increasing rate of hybrid rye replacement for corn on day 21, experiment 2[a].

| Item | Phase 1/2/3 corn replacement rate[b] | | | | | | *P* – values | |
|---|---|---|---|---|---|---|---|---|
| g/kg corn replacement: | 0/0/0 | 75/100/250 | 150/200/500 | 225/300/750 | 300/400/1000 | SE | Linear | Quadratic |
| Red blood cells, $\times 10^6$ /μL | 6.15 | 6.23 | 6.51 | 6.52 | 6.68 | 0.234 | 0.077 | 0.902 |
| Hemoglobin, g/dL | 9.80 | 9.59 | 9.93 | 9.96 | 10.04 | 0.253 | 0.296 | 0.773 |
| Packed cell volume, % | 32.48 | 31.94 | 32.63 | 33.48 | 33.56 | 0.846 | 0.174 | 0.658 |
| Mean corpuscular volume, fl | 53.14 | 51.45 | 50.73 | 51.80 | 50.25 | 1.704 | 0.321 | 0.747 |
| MCH[c], pg | 16.03 | 15.44 | 15.45 | 15.44 | 15.04 | 0.525 | 0.242 | 0.860 |
| MCHC[c], g/dL | 30.16 | 30.01 | 30.45 | 30.10 | 29.91 | 0.220 | 0.560 | 0.304 |
| Platelets, $\times 10^5$/μL | 5.43 | 6.22 | 6.67 | 5.74 | 6.53 | 0.630 | 0.346 | 0.508 |
| Total white blood cells[4], $\times 10^3$/μL | 21.30 | 20.50 | 20.79 | 22.91 | 23.19 | 1.790 | 0.263 | 0.539 |
| Neutrophils | 12.43 | 9.93 | 8.84 | 10.72 | 10.66 | 1.035 | 0.406 | 0.055 |
| Lymphocytes | 8.26 | 9.24 | 8.76 | 10.47 | 11.09 | 1.121 | 0.051 | 0.719 |
| Monocytes | 0.87 | 0.93 | 0.96 | 1.24 | 1.25 | 0.218 | 0.124 | 0.852 |
| Eosinophils | 0.42 | 0.23 | 0.36 | 0.22 | 0.12 | 0.097 | 0.066 | 0.793 |
| Basophils | 0.22 | 0.18 | 0.10 | 0.15 | 0.07 | 0.058 | 0.084 | 0.758 |
| Urea N, mg/dL | 9.38 | 7.75 | 8.13 | 7.38 | 10.13 | 0.954 | 0.712 | 0.040 |
| Albumin, g/dL | 2.24 | 2.30 | 2.30 | 2.25 | 2.33 | 0.088 | 0.655 | 0.940 |
| Total protein, g/dL | 3.83 | 4.14 | 4.01 | 4.03 | 4.00 | 0.097 | 0.443 | 0.146 |

[a] Least square means for dietary treatments represent 8 observations.
[b] The proportions (g/kg) indicate the amount of corn that was replaced with hybrid rye in the diets.
[c] MCH = Mean corpuscular hemoglobin; MCHC = Mean corpuscular hemoglobin concentration.

pigs (Bedford et al., 1992) and for 17-kg pigs (Thacker et al., 1999). Likewise, ADG and G:F were reduced when individually-housed pigs were fed diets containing 270 g/kg of rye at the expense of wheat during the initial 14 days of the experiment (Święch et al., 2012), and feed intake was also reduced when hybrid rye replaced wheat in diets for finishing pigs (Smit et al., 2019). The observation that feed intake was not reduced in the present experiment in phases 1 and 2 as a result of hybrid rye inclusion in the diet indicates that the low inclusion rates of rye in these diets did not have negative impact on feed intake. However, in phase 3, where rye inclusion was greater, feed intake was reduced with the intermediary hybrid rye levels, but not at the greatest hybrid rye level, which may have been a result of increased intestinal health in pigs fed the intermediary levels of hybrid rye as indicated by the reduced diarrhea scores observed in phase 1. The fact that G:F was reduced when the greatest amount of hybrid rye was fed in phase 3 was not surprising because hybrid rye contains less metabolizable energy than corn (McGhee and Stein, 2020), and pigs, therefore, consumed more feed to compensate for the reduced dietary energy in the diet with the greatest inclusion of hybrid rye. As illustrated by the diets used in this experiment, by including hybrid rye in diets instead of corn, dietary metabolizable energy will be reduced unless a high energy ingredient such as fat or oil is added to compensate for the lower metabolizable energy in hybrid rye. In formulation of diets for the present experiment it was decided not to add oil to the diets to maintain a constant metabolizable energy because of uncertainty about the metabolizable energy of fat fed to weanling pigs and addition of fat might, therefore, have confounded results.

In growing pigs, the dietary fiber from hybrid rye is more fermentable than fiber from corn and wheat (McGhee and Stein, 2020), and the abundance of fermentable arabinoxylans and fructo-oligosaccharides in rye may confer health benefits to animals (Bach Knudsen et al., 2005; Le Gall et al., 2009; Chuppava et al., 2020). Replacing portions of wheat with hybrid rye in diets for weanling pigs reduced the cecal prevalence and fecal shedding of *Salmonella* in experimentally infected pigs, which may have been a result of greater lactic acid and butyrate concentrations in the hindgut (Chuppava et al., 2020). Therefore, despite having limited fermentative capacity

**Table 8**
Blood analyses from pigs fed diets with increasing rate of hybrid rye replacement for corn on day 34, experiment 2[a].

| Item | Phase 1/2/3 corn replacement rate[b] | | | | | | *P* – values | |
|---|---|---|---|---|---|---|---|---|
| g/kg corn replacement: | 0/0/0 | 75/100/250 | 150/200/500 | 225/300/750 | 300/400/1000 | SE | Linear | Quadratic |
| Red blood cells, $\times 10^6$ /μL | 6.31 | 6.21 | 6.50 | 6.72 | 6.95 | 0.245 | 0.026 | 0.527 |
| Hemoglobin, g/dL | 10.94 | 10.29 | 11.06 | 11.25 | 10.94 | 0.324 | 0.357 | 0.942 |
| Packed cell volume, % | 35.05 | 34.60 | 36.19 | 36.01 | 35.76 | 1.176 | 0.451 | 0.759 |
| Mean corpuscular volume, fl | 55.76 | 55.89 | 54.85 | 53.73 | 51.50 | 1.312 | 0.014 | 0.336 |
| MCH[c], pg | 17.41 | 17.34 | 17.16 | 16.80 | 15.75 | 0.439 | 0.009 | 0.202 |
| MCHC[c], g/dL | 31.23 | 31.01 | 30.58 | 31.23 | 30.59 | 0.230 | 0.152 | 0.784 |
| Platelets, $\times 10^5$/μL | 4.99 | 4.82 | 2.87 | 5.46 | 5.06 | 0.458 | 0.595 | 0.966 |
| Total white blood cells[d], $\times 10^3$/μL | 18.86 | 17.39 | 14.93 | 17.22 | 18.95 | 1.613 | 0.998 | 0.061 |
| Neutrophils | 5.81 | 4.67 | 3.58 | 5.23 | 5.29 | 0.677 | 0.819 | 0.042 |
| Lymphocytes | 11.30 | 10.54 | 10.06 | 10.43 | 12.63 | 1.346 | 0.552 | 0.187 |
| Monocytes | 1.14 | 0.87 | 1.01 | 0.94 | 0.69 | 0.248 | 0.285 | 0.855 |
| Eosinophils | 0.09 | 0.20 | 0.25 | 0.15 | 0.18 | 0.066 | 0.531 | 0.170 |
| Urea N, mg/dL | 12.50 | 11.75 | 12.88 | 13.63 | 15.50 | 0.862 | 0.007 | 0.140 |
| Albumin, g/dL | 2.61 | 2.69 | 2.75 | 2.65 | 2.70 | 0.115 | 0.708 | 0.625 |
| Total protein, g/dL | 4.46 | 4.69 | 4.60 | 4.41 | 4.61 | 0.133 | 0.753 | 0.764 |

[a] Least square means for dietary treatments represent 8 observations.
[b] The proportions (g/kg) indicate the amount of corn that was replaced with hybrid rye in the diets.
[c] MCH = Mean corpuscular hemoglobin; MCHC = Mean corpuscular hemoglobin concentration.
[d] The concentration of basophils in blood samples was excluded from the table because the variable did not follow a normal distribution.

compared with growing pigs (Lallès et al., 2004), young pigs also appeared to benefit from being fed hybrid rye compared with wheat under challenged conditions.

Although rye contains more crude protein and amino acids than corn, the standardized ileal digestibility of amino acids is less in hybrid rye than in corn and the concentration of standardized ileal digestible amino acids is, therefore, similar in corn and hybrid rye (McGhee and Stein, 2018). As a consequence, when substituting hybrid rye for corn in a diet, the concentration of other amino acid-containing ingredients will not need to be adjusted if diets are formulated based on concentrations of standardized ileal digestible amino acids. However, because the concentration of crude protein is greater in hybrid rye than in corn, dietary crude protein will increase in diets containing hybrid rye, which was also illustrated in the present experiment. Excess protein in the hindgut may result in pathogenic bacterial proliferation, production of toxic compounds as a result of proteolytic fermentation, and increased incidence of diarrhea (Wellock et al., 2006; Heo et al., 2009; Gloaguen et al., 2014). However, the undigested protein from hybrid rye did not appear to negatively impact pigs in this experiment. In contrast, a reduction in the incidence of diarrhea was observed in phase 1 when pigs were fed modest inclusion of hybrid rye (60 or 90 g/kg), which may be due to improved intestinal health as a result of the greater concentration of fermentable fiber in hybrid rye compared with corn. The quadratic response in diarrhea incidence in phase 1 indicates that there may be an optimum level of dietary fiber that is effective in inhibiting pathogens in the intestinal tract and maximizing intestinal health, but this hypothesis needs to be confirmed in future research. However, the reduced neutrophils on day 34 in pigs fed diets with the intermediate levels of hybrid rye also indicate reduced innate immune system activation and inflammation (Fournier and Parkos, 2012). Dogs fed diets supplemented with fructooligosaccharides (which are present in hybrid rye) and mannanoligosaccharides had reduced neutrophils and elevated lymphocytes (Swanson et al., 2002). Neutrophil release into the blood is modulated by cytokines and chemokines, and T-cells are key producers of cytokines. Therefore, the changes in blood cell concentrations that were observed indicate that concentrations of blood cytokines may also be increased in pigs fed hybrid rye. However, the possible positive impacts on pig health of feeding hybrid rye to pigs after weaning warrants more investigation, especially under the stressors present at commercial farms.

## 5. Conclusions

Weanling pigs had preference for a diet based on corn compared with a diet based on a mixture of corn and hybrid rye. However, replacing up to 300, 400, or 1000 g per kg of corn in phase 1, 2, and 3 diets for weanling pigs did not result in differences in average daily gain or final body weight of pigs, but gain to feed ratio was reduced for pigs fed the diets with the greatest inclusion of hybrid rye because feed intake increased. The incidence of diarrhea was reduced in the first week after weaning if 60 or 90 g/kg hybrid rye was included in the diet, and differences in blood cell concentrations indicate that hybrid rye modulated the immune response of pigs differently than corn. More research is warranted to test if greater inclusion rates of hybrid rye can be included in diets during the initial 3 weeks after weaning without compromising growth.

## CRediT authorship contribution statement

**H.H. Stein**: Conceptualized the experiments. **M.L. McGhee**: Conducted the animal part of the experiments and summarized data. **H.H. Stein**: Contributed with data interpretation. **M.L. McGhee**: Wrote the first draft of the manuscript. **H.H. Stein**: Edited the final version of the manuscript. **H.H. Stein**: Supervised the project.

## Conflict of interest

The authors have no conflicts of interest.

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