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Non Ruminant Nutrition

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Hybrid rye may replace up to 75% of the corn in diets for gestating and lactating sows without negatively impacting sow and piglet performance

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Abstract

An experiment was conducted to test the hypothesis that hybrid rye can replace a part of the corn in gestation and lactation diets without negatively affecting sow and litter performance. For each phase, a corn–soybean meal diet and three diets in which hybrid rye replaced 25%, 50%, or 75% of corn were formulated. Two hundred sows were randomly allotted by parity to the four treatments. Results indicated that diet did not affect body weight or average daily gain (ADG) of sows or number of pigs born. The number of pigs weaned, litter weaning weight, and litter ADG increased and then decreased (quadratic, $P < 0.05$) as hybrid rye in diets increased. Pig mortality and number of crushed pigs tended (quadratic, $P < 0.10$) to be reduced as hybrid rye was added to the diet. Serum cytokines did not differ among treatments on day 105 of gestation or in pigs on the day of weaning, but interleukin (IL)-4, IL-10, and IL-18 on day 13 of lactation increased and then decreased (quadratic, $P < 0.05$) as hybrid rye inclusion increased in diets. Milk urea N increased (linear, $P < 0.05$) as hybrid rye was included in the diet, but no other differences in milk composition were observed. Overall, replacing 25% or 50% of corn with hybrid rye resulted in improved lactation performance, and replacing 75% of corn with hybrid rye resulted in sow and litter performance that was not different from that of sows fed control diets.

Key words: cereal grains, corn, hybrid rye, sows

Introduction

Rye is used in the human food industry for baking and distilling, as a substrate for biogas production, and as a livestock feed (Bengtsson et al., 1992; Bach Knudsen, 1997; Hübner et al., 2013; Balcerek et al., 2016). Rye is nutritionally similar to other cereal grains such as wheat and barley when considering concentrations of starch, protein, and fiber (Rodehutscord et al., 2016). Historically, rye has not been included in swine diets in large amounts due to concerns about ergot contamination and high concentrations of antinutritional factors, including alkylresorcinols, trypsin inhibitors, and nonstarch polysaccharides. However, newer varieties of hybrid rye contain fewer antinutritional factors (Schwarz et al., 2015), and the risk of ergot contamination is reduced with the advent of KWS PollenPlus (KWS, Lochow, Germany) that is incorporated into new hybrids of rye (Hackauf et al., 2012; Miedaner and Geiger, 2015).

Results of recent research in Denmark demonstrated that sows fed gestating and lactating diets containing hybrid rye performed as well as sows fed control diets based on barley, wheat, and soybean meal (Sørensen and Krogsdahl, 2017). However, there are currently no data from research in which the reproductive performance of sows fed hybrid rye was compared to that of sows fed corn, which is commonly used in the United States and other countries as part of corn–soybean meal diets. Although rye has greater concentrations

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Abbreviations

ADFI	average daily feed intake
ADG	average daily gain
IFN-γ	interferon gamma
IgG	immunoglobulin G
IL	interleukin
MUN	milk urea N
SCC	somatic cell count
TNF-α	tumor necrosis factor-α

of nonstarch polysaccharides than corn, mature pigs have a high capacity to ferment fiber (Jørgensen et al., 2007), and because the concentration of soluble dietary fiber is greater in rye than in corn (McGhee and Stein, 2020), it is likely that sows fed diets containing rye will have greater hindgut fermentation than sows fed diets based on corn. Indeed, greater intestinal and plasma concentrations of butyrate were demonstrated in pigs fed a rye-based diet than pigs fed a diet based on wheat (Bach Knudsen et al., 2005). Because butyrate is beneficial for intestinal health, it is possible that rye will positively influence sow immunity including circulating levels of cytokines, but data to demonstrate this have not been published. Thus, it was the objective of this research to test that the hypothesis replacement of some of the corn in diets for gestating and lactating sows will have positive impacts on sow lactation performance, litter growth performance, and concentrations of plasma cytokines.

Materials and Methods

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for the experiment. The experiment was conducted at the Swine Research Center at the University of Illinois from August 2018 to May 2019.

Experimental diets

Four gestation diets and four lactation diets were formulated to meet estimated requirements for gestating and lactating sows (NRC, 2012) using amino acid, P, and energy digestibility values in hybrid rye obtained in previous experiments (McGhee and Stein, 2018; 2019; 2020). Within each stage of production, the control diet was based on corn and soybean meal, and three additional diets in which hybrid rye replaced 25%, 50%, or 75% of the corn were formulated (Table 1). Diet samples were collected monthly, and at the conclusion of the experiment, samples were pooled and subsampled for chemical analysis. The hybrid rye used in the experiment was grown and cleaned of ergot in Minnesota in 2018, and after grinding via a hammer mill, ingredient samples were collected, pooled, and subsampled for analysis.

Animals, housing, and feeding

A total of 200 Camborough sows (PIC Camborough, Pig Improvement Company, Hendersonville, TN, USA) were bred to terminal line boars (PIC 359, Pig Improvement Company, Hendersonville, TN, USA), with 50 sows being randomly allotted within parity to each of the four treatments. Eleven to 20 sows were bred and farrowed at a time, and 11 groups of sows were, therefore, used. No gilts were included in the experiment. Feeding of gestation diets started within 7 d after breeding and continued until day 105 of gestation. At this time, sows were moved to the lactation facility and feeding of the lactation diets was initiated. During gestation and lactation, sows were housed individually in gestation stalls (2.1 × 0.6 m) and farrowing crates (2.1 × 1.5 m), respectively. Feed allotments for each sow were recorded on a daily basis. During the initial 90 d of gestation, sows were offered feed in the amount of 1.5 times the estimated requirement for metabolizable energy (i.e., 100 kcal metabolizable energy per kg body weight $^{0.75}$; NRC, 2012), but feed allowance was adjusted every other week, if needed, in order to maintain or achieve an ideal sow body condition by visual appraisal (approximately 3.0 on a 1- to 5-point scale; Patience and Thacker, 1989). From day 90 of gestation until farrowing, feed allowance was increased to 3.5 kg regardless of diet and sow parity. From farrowing until 4 d postfarrowing, all sows were offered 4.5 kg feed daily. From 4 d postfarrowing, and until weaning, all sows were offered feed on an ad libitum basis.

Table 1. Ingredient composition (as-is basis) of experimental diets in which 0%, 25%, 50%, or 75% of corn in a corn–soybean meal control diet was replaced with hybrid rye during gestation and lactation

	Gestation[1]				Lactation[1]			
Ingredient, %	0%	25%	50%	75%	0%	25%	50%	75%
Corn	69.88	52.43	34.97	17.50	67.73	50.79	33.88	16.95
Hybrid rye	–	17.48	34.97	52.47	–	16.95	33.88	50.86
Soybean meal	21.00	21.00	21.00	21.00	25.00	25.00	25.00	25.00
Soybean hulls	5.00	5.00	5.00	5.00	–	–	–	–
Soybean oil	1.00	1.00	1.00	1.00	4.00	4.00	4.00	4.00
Ground limestone	0.96	0.99	1.05	1.08	0.78	0.81	0.84	0.90
Dicalcium phosphate	1.50	1.45	1.36	1.30	1.70	1.65	1.60	1.50
L-lysine HCl, 78%	0.01	–	–	–	0.14	0.14	0.13	0.12
L-threonine, 98%	–	–	–	–	–	0.01	0.02	0.02
Sodium chloride	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
Choline	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Vitamin-mineral premix[2]	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

[1]The percentages indicate the amount of corn that was replaced with hybrid rye in the diets.
[2]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, 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, 1.26mg as ethylenediamine dihydriodide; Mn, 60.2 mg as manganese hydroxychloride; Se, 0.30mg as sodium selenite and selenium yeast; and Zn, 125.1mg as zinc hydroxychloride.

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Feed refusals were collected and measured daily from day 106 of gestation until 4 d postfarrowing and on the day of weaning. All litters were offered a standard creep feed diet from day 14 postfarrowing according to normal farm procedures.

Sow body weights were determined within 7 d of breeding, when sows were moved to the lactation barn, within 24 h after farrowing, and on the day of weaning. Weaning took place 19.51 ± 1.08 d postfarrowing. Number and weights of live born, still born, and mummified pigs were determined within 24 h of farrowing, and pigs were weighed again at weaning. Cross-fostering was completed within 24 h of farrowing, but pigs were only cross-fostered within treatment groups so that each sow had approximately 14 pigs. Following normal farm procedures, pigs weighing less than 0.8 kg at birth were considered low vitality and euthanized. Weights of pigs that died during the lactation period as well as the reason for death (crushed by sow, low vitality/starved, rupture, or euthanized due to congenital deformity) were recorded. Pigs were processed within 24 h of birth, and according to the normal farm procedures, processing included clipping needle teeth, docking tails, castrating male pigs, administering iron dextran and centiofur antibiotic (Excede, Zoetis, Parsippany, NJ, USA), and ear notching for identification.

Blood and milk sample collection

Blood samples were collected from 25 sows per treatment on day 105 of gestation and 22 d after moving from the gestation to the lactation facilities, which was approximately 13 d postfarrowing. Blood samples were also collected at weaning from the third heaviest barrow from each litter of the sows that were bled. Blood was collected in serum vacutainer tubes containing spray-coated silica as a serum clot activator. Blood was allowed to clot and then centrifuged at 4,000 × *g* for 13 min at room temperature. Serum was removed from centrifuged tubes and stored at −20 °C until analysis. In the same 25 sows from which blood samples were collected, milk samples were collected approximately 13 d postfarrowing following administration of 1 mL oxytocin (Bimeda-MTC Animal Health Inc., Cambridge, ON, Canada) intramuscularly. Approximately 25 mL of milk was collected from the first four functional teats on each side of the mammary gland, for a total of 50 mL of milk. Milk samples were stored at −20 °C immediately after collection. Prior to shipping milk for component analysis, all samples were thawed, placed in 60 mL tubes containing a milk preservative, and a subsample of 5 mL was placed in a separate tube for later analysis.

Chemical analyses

Diets and hybrid rye were analyzed for dry matter by oven drying at 135 °C for 2 h (method 930.15; AOAC Int., 2007) and for dry ash (method 942.05; AOAC Int., 2007). The gross energy in diets and hybrid rye was measured using an isoperibol bomb calorimeter (Model 6400, Parr Instruments, Moline, IL, USA). The crude protein was determined by measuring N (method 990.03; AOAC Int., 2007) using a Leco Nitrogen Determinator (model FP628, Leco Corp., St. Joseph, MI, USA). Total starch was analyzed by the glucoamylase procedure (method 979.10; AOAC Int., 2007), which yields the enzymatically hydrolyzed starch in the sample. Insoluble dietary fiber and soluble dietary fiber were analyzed according to method 991.43 (AOAC Int., 2007) using an Ankom TDF Fiber Analyzer (Ankom Technology, Macedon, NY, USA). Total dietary fiber was calculated as the sum of soluble dietary fiber and insoluble dietary fiber. Total acid-hydrolyzed ether extract was analyzed by acid hydrolysis using 3*N* HCl (Ankom^{HCl}, Ankom Technology, Macedon, NY, USA) followed by crude fat extraction using petroleum ether (Ankom^{XT15}, Ankom Technology, Macedon, NY, USA). Calcium and total P were measured by inductively coupled plasma optical emission spectroscopy (method 985.01 A, B, and C; AOAC, 2007) after wet ash sample preparation [method 975.03 B(b); AOAC Int., 2007]. Diets were analyzed for AA on a Hitachi Amino Acid Analyzer, Model No. L8800 (Hitachi High Technologies America, Inc.; Pleasanton, CA, USA) using ninhydrin for postcolumn derivatization and norleucine as the internal standard. Prior to analysis, samples were hydrolyzed with 6*N* 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].

Mycotoxins in corn and hybrid rye were analyzed at Trilogy Analytical Laboratories (Washington, MO, USA) using liquid chromatography–tandem mass spectroscopy. The following mycotoxins, with respective detection limits, were analyzed: 15-acetyl deoxynivalenol (0.1 mg/kg), 3-acetyl deoxynivalenol (0.1 mg/kg), aflatoxin B1 (0.001 mg/kg), aflatoxin B2 (0.001 mg/kg), aflatoxin G1 (0.001 mg/kg), aflatoxin G2 (0.001 mg/kg), citrinin (0.05 mg/kg), diacetoxyscirpenol (0.05 mg/kg), deoxynivalenol (0.1 mg/kg), fumonisin B1 (0.1 mg/kg), fumonisin B2 (0.1 mg/kg), fumonisin B3 (0.1 mg/kg), fusarenon X (0.1 mg/kg), neosolaniol (0.02 mg/kg), nivalenol (0.1 mg/kg), ochratoxin A (0.001 mg/kg), HT-2 toxin (0.005 mg/kg), T-2 toxin (0.005 mg/kg), and zearalenone (0.0125 mg/kg). Analysis of ergot alkaloids in rye was conducted by refractive index high performance liquid chromatography using Phenomenex Strata-X-CW (Phenomenex, Inc., Torrance, CA, USA) weak cation exchange and reversed phase column with a detection limit of 10 µg/kg.

Milk samples were analyzed by Eastern Laboratory Services (Medina, OH, USA) for the concentration of fat, free fatty acids, protein, milk urea N, lactose, other solids, total solids, and somatic cell count using a Milkoscan 7 calibrated for bovine milk (Foss, Hillerød, Denmark). The concentration of immunoglobulin G (IgG) in milk and serum samples was determined by enzyme-linked immunosorbent assay following the manufacturer's instructions (Bethyl Laboratories, Inc., Montgomery, TX, USA). The concentrations of interleukin (IL)-1α, IL-1β, IL-1 receptor antagonist, IL-2, IL-4, IL-6, IL-8, IL-10, IL-12, IL-18, interferon-γ (IFNγ), and tumor necrosis factor-α (TNF-α) in serum samples were measured via a porcine-specific multiplex immunoassay kit (MilliporeSigma, Burlington, MA, USA) and read with a Luminex MagPix instrument (Luminex Corporation, Austin, TX, USA).

Calculations and statistical analyses

At the conclusion of the experiment, data for body weight gain in gestation, body weight loss in lactation, average daily feed intake (ADFI) in gestation and lactation, estimated milk yield (calculated as 4 g milk per g of litter body weight gain; Close and Cole, 2000), and litter performance data were calculated. Litter performance data were calculated for each sow and included number of total born, live born, mummified, and still born pigs; number of pigs after cross-fostering; number of pigs weaned; and pig mortality rates (calculated as the percentage of live born pigs that died before weaning after adjusting for cross-fostering). Total litter birth weight, live litter birth weight, live litter birth weight after cross fostering, litter weight at weaning, and litter average daily gain (ADG) were calculated as well. Average pig weights and ADG were also calculated.

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Outliers were tested for using the UNIVARIATE procedure of SAS (SAS Institute Inc., Cary, NC, USA). Outliers were defined as observations with internally studentized residuals less than −3 or greater than 3. Of the 50 sows per treatment that were initiated on trial, 48 sows from the control treatment, 46 sows from the 25% rye treatment, 47 sows from the 50% rye treatment, and 47 sows from the 75% rye treatment completed the experiment. A sow was excluded from statistical analysis if fewer than five total pigs were born, or if three or more response variables were identified as outliers. Of the 188 sows that completed the experiment, seven sows were excluded from statistical analyses based on these criteria (one sow was excluded from the 25% rye treatment, and two sows were excluded from each of the other three treatments). After the removal of the seven extreme outlier sows, additional outlier observations for individual variables that remained in the data were also excluded from further analysis. Therefore, the number of observations per dietary treatment ranged from 42 to 46 for each variable.

Data related to pig mortality were analyzed using SAS Proc GLIMMIX with binomial distribution. All other data were analyzed using Proc MIXED after confirming normality of the residuals via Proc UNIVARIATE. The initial statistical model for both Proc MIXED and Proc GLIMMIX included the random effect of group and the fixed effects of diet, parity, and the interaction of diet and parity. However, the interaction of diet and parity was not significant (α = 0.05) for any variable, and therefore, a reduced model without the interaction term was used. The sow was the experimental unit for all data. Least square means were estimated for each mortality-related variable using the LSMEANS statement with inverse link option in Proc GLIMMIX. Data for milk somatic cell count and serum cytokines were transformed using base-10 log prior to analysis in Proc MIXED. Least square means for somatic cell count and cytokines were reported in the original scale after back-transforming (inverse log) the output from the LSMEANS statement in Proc MIXED. Least square means were reported for all other variables using the LSMEANS statement in Proc MIXED. Orthogonal contrast statements were used to test linear and quadratic effects of including graded levels of hybrid rye in the diets. Results were considered significant at $P \le 0.05$ and considered a tendency at $0.05 < P \le 0.10$.

Results

The analyzed composition of experimental diets and hybrid rye ingredient was within expected ranges (Table 2). Ergot alkaloids were not detected in the hybrid rye used in the experiment, but 10 µg/kg of HT-2 toxin were detected in the rye, and 0.1 mg/kg and 0.2 mg/kg of deoxynivalenol and fumonisin B1, respectively, were detected in the corn.

Differences in body weights of sows among treatment groups were not observed during gestation or lactation (Table 3), and there was no difference in ADG of sows among treatment groups during gestation or lactation. Although sows were fed according to metabolizable energy intake, which differed among diets, no difference in ADFI was observed during gestation. Sows fed diets in which 25% or 50% of the corn was replaced with hybrid rye consumed more feed in lactation than sows fed the other diets (quadratic, $P < 0.05$).

There were no differences among dietary treatments for number of total born pigs per litter, number of pigs born alive per litter, number of pigs per litter after cross-fostering, or number of still born pigs per litter (Table 4). Sows fed diets in which 25% or 50% of corn was replaced by hybrid rye tended to produce fewer mummified pigs than sows fed the other diets (quadratic, $P < 0.10$). There was an increase and then a reduction in the number of pigs weaned per litter as the inclusion of hybrid rye in the diets increased (quadratic, $P < 0.05$). Total litter birth

Table 2. Analyzed composition (as-is basis) of hybrid rye and of experimental diets in which 0%, 25%, 50%, or 75% of corn in a corn–soybean meal–based control diet was replaced with hybrid rye during gestation and lactation

	Gestation[1]				Lactation[1]				Hybrid
Item	0%	25%	50%	75%	0%	25%	50%	75%	rye
Dry matter, %	87.01	87.03	87.27	87.59	87.36	87.36	87.52	87.88	86.75
Ash, %	5.09	4.88	5.14	5.29	5.02	4.91	4.99	5.15	1.41
Gross energy, kcal/kg	3,764	3,744	3,765	3,744	3,959	3,932	3,946	3,966	3,790
Crude protein, %	14.94	14.97	16.67	16.84	15.73	16.31	16.65	17.46	10.17
Starch, %	43.64	42.35	45.60	43.08	54.69	48.07	48.22	44.22	58.82
Insoluble dietary fiber, %	12.50	13.70	14.70	17.60	10.80	11.60	11.70	12.50	13.40
Soluble dietary fiber, %	1.00	1.50	2.50	2.30	2.20	1.60	2.40	2.30	3.40
Total dietary fiber, %	13.50	15.20	17.20	20.00	12.90	13.20	14.00	14.90	16.80
Acid hydrolyzed ether extract, %	3.71	3.25	2.78	2.46	4.03	4.30	4.85	4.90	1.49
Ca, %	0.83	0.91	0.86	0.87	0.72	0.78	0.80	0.76	0.04
P, %	0.56	0.58	0.58	0.60	0.58	0.63	0.63	0.59	0.28
Arg, %	0.98	0.89	1.01	1.01	0.95	1.04	1.14	1.09	0.48
His, %	0.41	0.37	0.42	0.40	0.39	0.41	0.45	0.43	0.21
Ile, %	0.71	0.63	0.71	0.70	0.66	0.73	0.80	0.76	0.33
Leu, %	1.39	1.21	1.31	1.23	1.31	1.36	1.39	1.29	0.56
Lys, %	0.86	0.77	0.89	0.87	0.90	0.97	1.06	1.02	0.37
Met, %	0.23	0.21	0.24	0.23	0.23	0.24	0.25	0.25	0.15
Cys, %	0.26	0.23	0.28	0.27	0.24	0.26	0.29	0.29	0.21
Phe, %	0.80	0.73	0.83	0.81	0.76	0.83	0.90	0.87	0.42
Thr, %	0.59	0.53	0.61	0.59	0.57	0.62	0.66	0.66	0.30
Trp, %	0.17	0.17	0.17	0.18	0.17	0.17	0.20	0.19	0.08
Val, %	0.78	0.71	0.79	0.79	0.73	0.80	0.87	0.85	0.45

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

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weight tended to increase and then decrease as the inclusion of hybrid rye in the diets increased (quadratic, $P < 0.10$), but live litter birth weight was not affected by diet. An increase and then a reduction in the litter wean weight as the inclusion of hybrid rye in the diets increased was also observed (quadratic, $P < 0.05$). Litter ADG increased and then decreased as hybrid rye was added to the diet (quadratic, $P < 0.05$). No differences were observed for individual pig weights, but individual pig ADG decreased (linear, $P < 0.05$) as more hybrid rye was included in the diet. Preweaning mortality tended to be reduced (quadratic, $P < 0.10$) as hybrid rye was added to the diets, as did the proportion of pigs crushed by sows ($P < 0.10$).

Composition of milk on day 13 of lactation was not influenced by diet (Table 5), with the exception that a linear increase ($P < 0.05$) in milk urea N was observed as dietary hybrid rye inclusion increased. Milk somatic cell count tended to increase as rye inclusion increased (quadratic, $P < 0.10$), but no difference among treatments was observed for IgG in milk on day 13 of lactation.

Serum IgG in sows did not differ among treatments on day 105 of gestation and the same was true for all measured cytokines and chemokines (Table 6). However, on day 13 of lactation, serum IgG tended ($P < 0.10$) to be reduced as hybrid rye levels in the diet increased. As hybrid rye in the diet increased, there was an increase and then a reduction (quadratic, $P \leq 0.05$) for IL-4, IL-10, and IL-18 in serum from sows on day 13 of lactation. Similarly, on day 13 of lactation IL-1α, IL-1 receptor antagonist, IL-6, and TNF-α tended to increase and then decrease as hybrid rye inclusion in the diet increased (quadratic, $P < 0.10$). Serum samples obtained from pigs at weaning did not differ in concentration of IgG, but IL-2 tended to increase and then decrease (quadratic, $P < 0.10$) as hybrid rye inclusion in the sow diet increased (Table 7). No other differences were observed in serum from pigs at weaning.

Discussion

Hybrid rye may replace barley and wheat in gestation diets (up to 60% hybrid rye inclusion) and in lactation diets (up to 35% hybrid rye inclusion) without influencing sow reproductive or litter performance (Sørensen and Krogsdahl, 2017), but to the best of our knowledge, no data for effects of substituting hybrid rye for corn in diets for sows have been reported. Hybrid rye has a greater concentration of soluble fiber than corn and is in that respect more similar to barley than to corn (McGhee and Stein, 2018; 2020), and it is therefore not known if hybrid rye can substitute corn in diets for sow with the same results as if wheat and barley are substituted. However, because sows have a high capacity to ferment fiber (Jørgensen et al., 2007), it was hypothesized that hybrid rye could replace corn with minimal impact on sow or litter performance. It was also hypothesized that the specific fiber composition of hybrid rye may confer health benefits to sows because the inulin-type fructans, soluble arabinoxylans, and mixed-linked β-glucans in hybrid rye are considered prebiotics (Bach Knudsen and Lærke, 2010; Gibson et al., 2010; Mendis et al., 2016; Cheng et al., 2020).

Hybrid rye contains less metabolizable energy than corn as determined in growing pigs (approximately 230 kcal/kg dry matter; McGhee and Stein, 2020); therefore, if ADFI is equal, ADG of pigs fed hybrid rye would be expected to be reduced compared with pigs fed corn. However, in the present experiment, ADFI and ADG in gestation did not differ among treatments, indicating the difference in metabolizable energy between corn and hybrid rye is less when fed to sows compared with growing pigs due to the greater capacity for fermentation of fiber in sows. The lack of differences among treatments for litter size at birth and in sow blood characteristics in late gestation indicates that sows were unaffected by gestation dietary treatment. The implication of this observation is that hybrid rye may replace at least 75% of the corn in gestation diets for sows without impacting gestational performance.

Gestating sows are most often limit-fed to avoid problems associated with over conditioning, whereas sows in lactation are fed near or at ad libitum to maximize milk production and prevent excess mobilization of body tissue reserves (Quesnel et al., 2009; Guillemet et al., 2010; Loisel et al., 2013). The observation that sow body weights did not differ among

Table 3. Performance of sows fed diets in which 0%, 25%, 50%, or 75% of corn from a corn–soybean meal–based control diet was replaced with hybrid rye during gestation and lactation[1]

	Diet[2]					P-values	
Item	0%	25%	50%	75%	SEM	Linear	Quadratic
Parity	1.49	1.52	1.45	1.52	0.204	0.981	0.917
Body weight, kg							
Day 7 gestation	228.3	231.7	226.9	226.5	3.06	0.293	0.376
Day 105 gestation	297.8	300.0	298.3	294.2	3.60	0.296	0.253
Day 1 lactation	284.4	287.1	285.1	285.1	3.37	0.990	0.583
Day 20 lactation	262.2	263.8	260.2	259.7	3.65	0.358	0.701
Average daily gain, kg							
Day 7 to 105 gestation	0.725	0.707	0.737	0.717	0.022	0.934	0.961
Day 1 to 20 lactation	−1.15	−1.21	−1.27	−1.20	0.094	0.461	0.367
Average daily feed intake, kg							
Day 7 to 105 gestation	2.90	2.93	2.93	2.94	0.047	0.190	0.466
Pre-farrowing[3]	3.30	3.34	3.27	3.33	0.040	0.723	0.746
Day 1 to 20 lactation	4.93	5.23	5.15	4.97	0.181	0.934	0.031
Estimated total milk yield[3], kg	196.9	205.9	206.9	191.4	6.26	0.508	0.021
Estimated daily milk yield, kg	11.35	11.72	11.83	10.86	0.365	0.292	0.022

[1]Least square means for each dependent variable represent 42 to 46 observations per treatment after the removal of outliers.
[2]The percentages indicate the amount of corn that was replaced with hybrid rye in the diets.
[3]Day 106 of gestation until farrowing.
[3]Estimated milk yield was calculated as 4 g milk per 1 g of litter body weight gain (Close and Cole, 2000).

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Table 4. Performance of litters from sows fed diets in which 0%, 25%, 50%, or 75% of corn in a corn–soybean meal–based control diet was replaced with hybrid rye during gestation and lactation[1]

	Diet[2]					P-values	
Item	0%	25%	50%	75%	SEM	Linear	Quadratic
Pigs per litter, *n*							
Total born	16.18	16.59	16.12	15.59	0.566	0.308	0.336
Born alive	14.06	14.74	14.23	13.82	0.521	0.547	0.232
After cross-fostering	14.01	14.80	14.12	13.77	0.414	0.383	0.115
Still born	1.74	1.55	1.63	1.25	0.226	0.114	0.568
Mummified	0.27	0.14	0.11	0.37	0.102	0.616	0.019
Weaned	11.29	12.23	12.00	11.40	0.349	0.953	0.011
Litter weight, kg							
Total at birth	22.70	22.75	23.35	21.41	0.664	0.203	0.086
Live at birth	20.16	20.51	20.68	19.56	0.671	0.554	0.217
After cross-fostering	20.02	20.39	20.24	19.58	0.580	0.522	0.310
At weaning	69.21	71.91	72.61	67.45	1.877	0.532	0.018
Litter average daily gain, kg	2.84	2.93	2.96	2.71	0.086	0.292	0.022
Individual pig weight, kg							
Live or dead at birth	1.45	1.40	1.43	1.42	0.040	0.681	0.575
Live at birth	1.46	1.42	1.45	1.45	0.040	0.937	0.516
At weaning	6.20	5.96	6.05	5.96	0.137	0.184	0.518
Pig average daily gain, kg	0.273	0.259	0.260	0.257	0.007	0.048	0.339
Pig mortality[3], %							
Died prior to weaning	18.73	15.47	13.81	16.25	1.778	0.204	0.073
Crushed by sow	8.02	5.46	4.96	6.04	1.235	0.170	0.077
Low vitality/starved	7.58	7.86	5.45	7.58	1.224	0.599	0.362
Rupture	1.65	1.63	2.45	2.41	0.718	0.259	0.997

[1]Least square means for each variable represent 43 to 46 observations per treatment after the removal of outliers.
[2]The percentages indicate the amount of corn that was replaced with hybrid rye in the diets.
[3]Mortality was calculated as the percentage of live born pigs that died before weaning after adjusting for cross-fostering

Table 5. Composition of milk samples collected approximately 13 d postfarrowing from sows fed diets in which 0%, 25%, 50%, or 75% of corn in a corn–soybean meal–based control diet was replaced with hybrid rye during gestation and lactation[1]

	Diet[2]					P-values	
Item	0%	25%	50%	75%	SEM	Linear	Quadratic
Fat, %	8.08	8.25	8.00	7.83	0.314	0.344	0.486
Free fatty acids, %	0.313	0.357	0.307	0.337	0.031	0.855	0.807
Protein, %	4.44	4.45	4.49	4.40	0.072	0.746	0.381
MUN[3], mg/dL	48.81	47.99	49.55	52.20	1.303	0.012	0.097
Lactose, %	5.67	5.76	5.70	5.72	0.048	0.609	0.337
Other solids, %	6.51	6.59	6.54	6.55	0.047	0.608	0.351
Total solids, %	19.06	19.14	19.02	18.81	0.303	0.415	0.537
SCC[3], × 1,000/mL	170	182	73	281	65.7	0.719	0.080
IgG[3], mg/mL	0.504	0.448	0.487	0.435	0.038	0.176	0.952

[1]Least square means for dietary treatments represent 25 observations.
[2]The percentages indicate the amount of corn that was replaced with hybrid rye in the diets.
[3]MUN, Milk urea N; SCC, Somatic cell count; IgG, Immunoglobulin G.

treatments during the experiment supports the hypothesis that sow performance was not negatively affected by the inclusion of hybrid rye in the diets. Inclusion of fibrous ingredients in gestation diets may better prepare sows for full feeding in lactation due to their greater bulk density and lower energetic value (Matte et al., 1994; Farmer et al., 1996; Quesnel et al., 2009; Loisel et al., 2013), which may explain why sows fed 25% or 50% hybrid rye replacement diets consumed more feed than sows fed the corn control diet during lactation. However, sows fed the greatest amount of hybrid rye did not follow the trend of greater feed intake during lactation, indicating that sows became more quickly satiated or stayed satiated longer when hybrid rye was fed at a high inclusion rate. Similar results for reduced feed intake of diets with high inclusion of hybrid rye have been observed in growing and finishing pigs (Smit et al., 2019). The observation that the number of pigs weaned, litter weight at weaning, and litter ADG were greater if 25% or 50% of corn was replaced by hybrid rye indicates that hybrid rye may positively influence sow metabolism or health, which may have resulted in improved performance. In combination with increased sow feed intake and increased estimated milk yield contributing to heavier pigs at weaning, the higher-yielding treatment groups also tended to have reduced preweaning litter mortality. It is possible that the satiating effects of dietary fiber

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Table 6. Serum immune response of sows fed diets in which 0%, 25%, 50%, or 75% of corn in a corn–soybean meal control diet was replaced with hybrid rye during gestation and lactation[1]

	Diet[2]					P-values	
Item	0%	25%	50%	75%	SEM	Linear	Quadratic
Day 105 of gestation							
IgG[3], mg/mL	17.51	18.48	15.94	17.15	2.315	0.514	0.926
IL-1α[3], ng/mL	0.33	0.43	0.29	0.33	0.069	0.535	0.567
IL-1β, ng/mL	1.53	2.25	1.68	1.62	0.435	0.891	0.291
IL-1RA[3], ng/mL	1.41	2.07	1.33	1.51	0.355	0.761	0.452
IL-2, ng/mL	1.81	2.73	1.75	1.96	0.445	0.773	0.361
IL-4, ng/mL	7.63	11.72	7.03	8.13	2.555	0.752	0.543
IL-6, ng/mL	0.82	1.33	0.77	0.95	0.256	0.903	0.509
IL-8, ng/mL	0.11	0.14	0.07	0.11	0.022	0.362	0.866
IL-10, ng/mL	3.19	5.01	3.15	3.43	0.908	0.771	0.346
IL-12, ng/mL	1.28	1.62	1.14	1.28	0.206	0.501	0.623
IL-18, ng/mL	5.05	7.01	5.07	5.19	1.249	0.745	0.380
IFN-γ[3], ng/mL	21.02	29.14	21.39	25.52	9.251	0.816	0.775
TNF-α[3], ng/mL	0.25	0.42	0.21	0.27	0.100	0.686	0.630
Day 13 of lactation							
IgG, mg/mL	17.97	19.41	15.15	15.44	2.191	0.060	0.679
IL-1α, ng/mL	0.34	0.55	0.45	0.41	0.079	0.558	0.053
IL-1β, ng/mL	2.23	2.80	2.86	2.64	0.443	0.418	0.301
IL-1RA, ng/mL	1.57	2.62	2.22	2.16	0.404	0.269	0.096
Day 13 of lactation							
IL-2, ng/mL	2.08	3.36	2.90	2.91	0.495	0.206	0.125
IL-4, ng/mL	9.00	17.28	13.20	10.90	3.100	0.741	0.050
IL-6, ng/mL	1.18	1.62	1.65	1.19	0.269	0.944	0.053
IL-8, ng/mL	0.11	0.18	0.13	0.12	0.032	0.999	0.119
IL-10, ng/mL	3.67	6.45	5.35	4.56	1.046	0.547	0.045
IL-12, ng/mL	1.30	1.86	1.67	1.58	0.264	0.415	0.129
IL-18, ng/mL	5.68	9.19	8.39	7.03	1.460	0.439	0.046
IFN-γ, ng/mL	32.79	59.66	52.72	45.94	12.535	0.366	0.102
TNF-α, ng/mL	0.38	0.68	0.50	0.30	0.164	0.420	0.058

[1]Least square means for dietary treatments represent 19 to 23 observations.
[2]The percentages indicate the amount of corn that was replaced with hybrid rye in the diets.
[3]IgG, Immunoglobulin G; IL, interleukin; IL-1RA, IL-1 receptor antagonist; IFNγ, interferon-gamma; TNF-α, tumor necrosis factor-α.

from hybrid rye may have resulted in sows exhibiting fewer postural changes, which has been previously demonstrated in sows fed highly fermentable fibrous diets (de Leeuw et al., 2004). This hypothesis was supported by the observed tendency for fewer pigs crushed, but because no behavioral observations to reflect postural changes were recorded, this hypothesis cannot be verified from the present data. The fewer crushed pigs may also have been due to greater pig vigor as a result of increased colostrum and milk intake.

Fiber from hybrid rye is more fermentable than fiber from corn in growing pigs (McGhee and Stein, 2020) and the same is likely true in sows. Fermentation of rye fiber increases the production of the short chain fatty acid butyrate in the large intestine (Bach Knudsen et al., 2005). Butyrate is the preferred energy source for colonocytes, supporting maintenance and function of the colon (Roediger, 1980), and butyrate may also improve intestinal mucosa health and barrier function in the colon, as well as decrease inflammation (Hamer et al., 2008; Vogt et al., 2014). It was hypothesized in the present experiment that if the fermentation of hybrid rye fiber and subsequent production of butyrate had positive effects on gut health of sows, the concentration of pro-inflammatory cytokines in serum from sows and pigs fed diets containing hybrid rye would be reduced, whereas anti-inflammatory cytokines would be elevated.

Butyrate stimulates production of anti-inflammatory cytokines IL-10 and IL-4 in human cells (Säemann et al., 2000), which may explain the observation of elevated IL-10 and IL-4 in serum from sows fed diets in which 25% or 50% of the corn was replaced by hybrid rye. Butyrate, through inhibition of NF-κB, also has inhibitory effects on production of pro-inflammatory cytokines including IL-1β, IL-6, IL-8, IL-12, IFN-γ, and TNF-α (Säemann et al., 2000; Pandey and Agrawal, 2006; Chen et al., 2019), but these effects were not observed in the present experiment. It is possible the serum obtained from jugular veins of sows in the present experiment may not fully explain the localized effects of butyrate within the intestine (Milo et al., 2002). For example, supplemented butyrate exerted opposite effects on cytokine production in the small intestine compared with the large intestine in weanling pigs (Grilli et al., 2016).

Because no differences were observed among treatments for concentrations of cytokines in late gestation, it is possible that the increased concentrations of pro-inflammatory cytokines IL-1α, IL-6, IL-18, and TNF-α are associated with lactation stressors rather than being a direct effect of hybrid rye. In dairy cows, a moderate inflammatory response is required for protecting against pathogens and regulating nutrient metabolism during the transition period from late gestation to early lactation (Bradford et al., 2015). Onset of lactation also triggers an increased inflammatory response in sows, particularly in the liver (Rosenbaum et al., 2012; Gessner et al., 2015). Sows fed diets in which 25% or 50% corn was replaced by hybrid rye had greater nutritional demand for milk production,

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Table 7. Serum immune response of 20-d old pigs farrowed from sows fed diets in which 0%, 25%, 50%, or 75% of corn in a corn–soybean meal control diet was replaced with hybrid rye during gestation and lactation[1]

	Diet[2]					P-values	
Item	0%	25%	50%	75%	SEM	Linear	Quadratic
IgG[3], mg/mL	6.60	6.75	6.36	6.98	1.090	0.852	0.789
IL-1α[3], ng/mL	0.18	0.21	0.13	0.15	0.050	0.316	0.968
IL-1β, ng/mL	0.67	1.03	0.74	0.53	0.252	0.338	0.131
IL-1RA[3], ng/mL	0.67	0.93	0.66	0.61	0.184	0.427	0.252
IL-2, ng/mL	0.76	1.36	0.98	0.65	0.328	0.495	0.078
IL-4, ng/mL	1.96	3.75	2.76	1.92	1.326	0.834	0.210
IL-6, ng/mL	0.44	0.60	0.31	0.30	0.138	0.135	0.516
IL-8, ng/mL	0.14	0.16	0.16	0.17	0.030	0.338	0.793
IL-10, ng/mL	1.52	2.11	1.51	1.35	0.522	0.537	0.397
IL-12, ng/mL	0.90	0.97	0.77	0.75	0.135	0.128	0.676
IL-18, ng/mL	2.61	3.38	2.60	2.37	0.709	0.532	0.384
IFN-γ[3], ng/mL	18.54	17.38	16.19	11.48	4.443	0.150	0.549
TNF-α[3], ng/mL	0.22	0.35	0.20	0.17	0.067	0.208	0.195

[1]Least square means for dietary treatments represent 20 to 21 observations. Serum samples were obtained on day 20 of lactation from the third heaviest barrow of each litter.
[2]The percentages indicate the amount of corn that was replaced with hybrid rye in the diets.
[3]IgG, Immunoglobulin G; IL, interleukin; IL-1RA, IL-1 receptor antagonist; IFNγ, interferon-gamma; TNF-α, tumor necrosis factor-α.

which likely required both greater feed intake and mobilization of body reserves (Strathe et al., 2017). Thus, these sows may have undergone greater changes in liver metabolism and experienced heightened inflammatory responses corresponding with the elevated proinflammatory cytokines observed on day 13 of lactation. Despite contradicting observations of both elevated pro-inflammatory and anti-inflammatory cytokines, few differences in cytokine concentrations were detected in pigs at the time of weaning, indicating that the immune status of sows did not directly impact the quantified immune markers in average-weight pigs from their litters.

Conclusion

Replacing corn with hybrid rye in gestation and lactation diets had no effect on sow body weight changes or on the number or birth weight of pigs. In gestation, up to 75% of corn may be replaced by hybrid rye without negative impacts on sow reproductive performance. Lactation diets in which 25% or 50% of corn was replaced by hybrid rye resulted in improved sow lactation performance including weaning of larger and heavier litters due to reduced preweaning mortality and increased milk yield. Replacing 75% of corn with hybrid rye in lactation diets did not benefit sow or litter performance, but resulted in litter sizes not different from those of sows fed the corn-soybean control diet. Future research should focus on determining effects of hybrid rye on butyrate synthesis, intestinal health, and milk production and determination of the impact of hybrid rye on sow behavior in lactation is also warranted.

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Conflict of interest statement

The authors declare no real or perceived conflicts of interest.

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